ACTIVE STRUCTURAL ACOUSTIC CONTROL (ASAC)

FINAL TECHNICAL REPORT

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This final report for the Office of Naval Research Grant N00014-92-J-1170 concerns further VPI&SU research to develop and refine active structural acoustic control (ASAC) with active/adaptive structures. The focus is on the development and demonstration of advanced system design and optimization techniques for complex structures and disturbances, and realistic system implementations. This required a highly coordinated analytical and experimental research effort in the three areas of structural acoustics, actuators and sensors and control algorithms. These efforts include further development and refinement of promising new directions from a previous Grant. Significant progress and innovations have been made in structural acoustics, actuators, sensors, control approaches, and related design optimization techniques. Due to the coupled nature of the problem, considerable effort has been given to the interaction of these areas with each other, and their integration for realistic disturbances and applications. The investigations have focused on the use of distributed control forces (e.g., distributed piezoelectric strain actuators) and sensors (PVDF), and DSP controllers. Demonstrated technology advancements are highly applicable to acoustic quieting in advanced naval vessel designs in the low frequency range from 10 Hz to 1 kHz.

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ABSTRACT

This final technical report for Office of Naval Research Grant N00014-92-J-1170 concerns further VPI&SU research to develop and refine active structural acoustic control (ASAC) with active/adaptive structures. The focus is on the development and demonstration of advanced system design and optimization techniques for complex structures and disturbances, and realistic system implementations. This required a highly coordinated analytical and experimental research effort in the three areas of structural acoustics, actuators and sensors and control algorithms. These efforts include further development and refinement of promising new directions from a previous Grant. Significant progress and innovations have been made in structural acoustics, actuators, sensors, control approaches, and related design optimization techniques. Due to the coupled nature of the problem, considerable effort has been given to the interaction of these areas with each other, and their integration for realistic disturbances and applications. The investigations have focused on the use of distributed control forces (e.g., distributed piezoelectric strain actuators) and sensors (PVDF), and DSP controllers. Demonstrated technology advancements are highly applicable to acoustic quieting in advanced naval vessel designs in the low frequency range from 10 Hz to 1 kHz.

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EXECUTIVE SUMMARY

This research for the Office of Naval Research (ONR) Grant N00014-92-J-1170 in the area of Active Structural Acoustic Control (ASAC) with active/adaptive structures has spanned three years of effort at VPI&SU. The focus has been on the development and demonstration of advanced system design techniques for complex structures and disturbances, and realistic system implementations and considerations. This required a highly coordinated analytical and experimental research effort in the three areas of structural acoustics, actuators and sensors and control algorithms. These efforts include further development and refinement of promising research initiated under a previous three year Grant from the DARPA/ONR Advanced Submarine Technology (AST) Program (N00014-88-K-0721). The results show that significant progress and innovations have been made in structural acoustics, actuators, sensors, control approaches, and related design optimization techniques. Due to the coupled nature of the problem, considerable effort throughout the VPI&SU program has been given to the interaction of these areas with each other, and their integration for realistic disturbances and applications. The investigations have focused on the use of distributed control forces (e.g., distributed piezoelectric strain actuators) and sensors (PVDF), and digital signal processor (DSP) controllers. Structurally radiated noise controlled by active/adaptive means applied directly to the structure should be highly applicable to acoustic quieting in advanced naval vessel designs.

The key technical accomplishments under this Grant have advanced the state-of-the-art in structural acoustics, adaptive materials and structures, and active control. Concisely some important accomplishments are:

1. Application of real-time broadband wavenumber transforms to planar and cylindrical structures thus eliminating the need for the need for far-field sensing of the radiated sound pressure.

2. Broadband control of sound radiation from panels with integrated optimally designed actuators and sensors over the frequency range between 0 to 500 Hz.

3. Actuator and sensor design for ASAC by eigenfunction assignment extending it to MIMO feedforward controlled systems.

4. Development of FEM/BEM based efficient optimization system design approaches for ASAC with statistical diagnostics.

5. Application of hybrid structural feedforward and feedback control techniques for control of broadband acoustics to account for transient disturbances.

6. Continued development of design approaches and algorithms for the optimal placement of point force and distributed PZT actuators for actively controlling acoustic radiation from plates, cylinders, and more complex structures than in the previous research program.

7. Development of related design techniques for the optimal placement of point accelerometer, and distributed PVDF sensors for single and multiple frequency excitation.

8. Developed optimal design approaches using FEM/BEM for complex structures under multiple frequency excitation.

9. Developed a model for active control of sound radiation from a coupled cylinder-raft system using passive-active isolation mounts.

10. Developed an eigenanalysis approach for designing shaped PVDF distributed structural acoustic sensors

11. Extended the capability of the NASHUA numerical structural acoustic model to address active control approaches for fluid loaded structures.

12. Established an electro-mechanical impedance theory for distributed strain actuation of active structures with experimental verification.

13. Application of the electro-mechanical impedance theory to determine system power flow, and to design energy efficient active control structures.

14. Investigated electro-mechanical impedance theory for active structures with multiple coupled actuators.

15. Active noise control with PVDF-foam composites combining passive and active control.

16. Developed approaches to reduce the effect of aliasing in wavenumber sensing using point sensors.

17. Development of simultaneous sensing and actuation for a single piezoelectric element that provides truly collocated active control of acoustic properties.

Results of this research have been presented in 63 technical papers (including 32 papers in refereed journals), and 16 talks at symposia and conferences. The technical papers are found in Appendix C (separate enclosure).

1.0 INTRODUCTION

This is the final technical report for Office of Naval Research (ONR) Grant N00014-92-J-1170. It addresses Virginia Polytechnic Institute and State University (VPI&SU) research in the area of Active Structural Acoustic Control (ASAC) with active/adaptive structures for naval applications that has spanned three years. The focus has been on the development and demonstration of advanced system design techniques for complex structures and disturbances, and realistic system implementations and considerations. These efforts include further development and refinement of promising research initiated under a previous three year ONR Grant (N00014-88-K-0721) as part of the DARPA/ONR Advanced Submarine Technology Program (AST). The report is divided into progress in structural acoustics, actuators, sensors, control approaches and related design techniques. The results show that significant progress and innovations have been made in structural acoustics, actuators, sensors, control approaches, and related design optimization techniques. Due to the coupled nature of the problem, considerable effort throughout the VPI&SU program has been given to the interaction of these areas with each other, and their integration for realistic disturbances and applications. The investigations have focused on the use of distributed control forces (e.g., distributed piezoelectric strain actuators) and sensors (PVDF), and digital signal processor (DSP) controllers. Structurally radiated noise controlled by active/adaptive means applied directly to the structure should be highly applicable to acoustic quieting in advanced naval vessel designs.

1.1 STATEMENT OF WORK

A concise statement of work for this research program is:

> "Further develop and refine the Active Structural Acoustic Control (ASAC) technique with the threefold aim of (1) extend research in important areas established in the previous ONR Grant; (2) develop on promising new directions established in the previous project; (3) extend research to complex structures and more realistic design applications. This is to involve a highly coordinated analytical and experimental research in the three areas of structural acoustics, actuators and sensors and control algorithms."

This research task was divided into analytical and experimental efforts. The period of performance for this Grant was from 1 September 1991 to 31 August 1994. The Scientific Program Officer at ONR was Dr. Kam W. Ng.

1.2 PROGRAM ORGANIZATION

This section presents the organization of this research program at VPI&SU, and discusses associated cooperative programs. Professor Chris R. Fuller is the Principal Investigator for this research program, and he is assisted by several other faculty co-investigators and staff members as shown in the organization chart illustrated in Figure 1. This chart shows the top level structure of the program organization, and the primary faculty and staff members with their respective functions.

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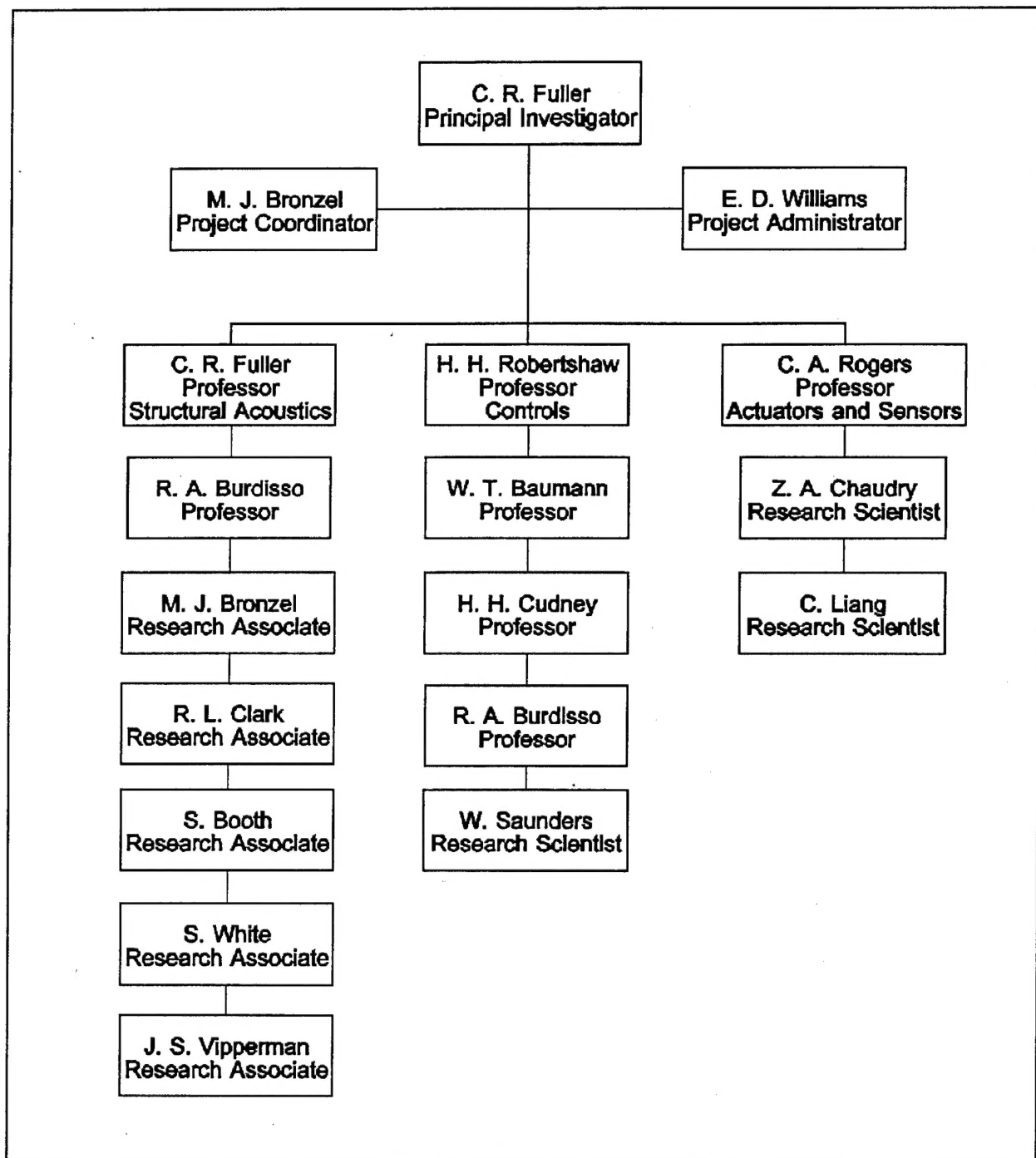
Figure 1 VPI&SU Active Structural Acoustic Research Program Organization.

The key participants are in the Mechanical Engineering Department (ME) at VPI&SU, and they are assisted by members of the Electrical Engineering Department (EE), and the Center for Intelligent Materials (CIMSS) as shown. General structure of this organization is based upon the critical technologies for active structural acoustic control, and the individual assignments reflect well-established expertise in the respective technologies and functional requirements. A tabulation of all the VPI&SU participants provided in Appendix A additionally lists students and their degree programs.

Cooperative Research Programs

A goal in this project has been cooperation with centers of excellence that are performing related research work. Participation of staff from centers at VPI&SU was with the view of widening the base and strength of the program. Within VPI&SU this has involved the Center for Intelligent Material Systems and Structures, and the Fiber & Electro-Optics Research Center.

With the formal approval of ONR and other organizations there has been a continuing productive and cooperative effort with other research programs outside VPI&SU that involve similar technical interests and complimentary resources. In brief, these cooperative programs are:

- NASA Langley Research Center - Exchange of LMS control methodologies and experimental implementation.

- University of Adelaide, Australia - Exchange of faculty/students working in the areas of active structural acoustics.

- Naval Surface Warfare Center, Carderock Division - Development of control module for NASHUA, use of computers, loan of equipment, and exchange of information on the subject of fluid loaded structural modeling.

AASERT Program

VPI&SU actively participates in supporting the education of students from a minority background, and this research project has received additional support from the Augmentation Awards for Science and Engineering Research Training (AASERT) program. Recruiting minority students is achieved through a cooperative program established between VPI &SU and the University of Puerto Rico, Mayaguez Campus. AASERT graduate students who are competitively selected work with other students at VPI&SU in the ASAC research project.

1.3 REPORT ORGANIZATION

The organization of this report presents the rationale for this research and the progress made in the important areas of structural acoustics, actuators, sensors, and control approaches. The next section (2.0) presents the technical background and rationale for active structural acoustic control, the

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state-of-the-art at the beginning of this research, VPI&SU's historical involvement, and the specific research objectives and goals of this research program. Section 3.0 presents an overview of active structural acoustics, and involved technologies. Sections 4, 5, and 6 address the research progress made in structural acoustics, actuators, and sensors respectively. Both state feedback and LMS adaptive feedforward control techniques are discussed in Section 7. Section 8 addresses the application and transfer of these developed technologies to practical problem areas, and advanced designs. Section 9 presents the future directions of the continuing research in terms of the goals and perceived problems at the conclusion of the reported research. Section 10 gives a summary and the conclusions that can be drawn from the research undertaken. The last section (Section 11) is the reference list for this final technical report. Appendices A and B are included to show project participants, and a bibliography of technical papers and talks supported by this research Grant. Appendix C enclosed separately contains copies of the actual papers published.

2.0 BACKGROUND

In many applications the sound fields radiated by vibrating elastic structures is an important noise problem. Examples are machinery noise in factories, marine hull radiated noise and interior noise in aerospace applications. Of particular interest is naval vessel structural acoustic radiation where there is a requirement for extreme levels of quietness, and it additionally represents a situation with seawater fluid loading and propagation. Understanding the behavior of such systems, with a view to controlling them, involves the field of structural acoustics. Structural acoustics is the study of how elastic structures radiate or receive sound [1], and in its most fundamental form involves the simultaneous solution of the differential equations describing the structure and fluid media with appropriate coupling conditions between the two (a "fully coupled" analysis).

The usual methods of control of such radiated noise fields involve passive techniques such as added mass, damping, stiffness and system modification through redesign. However, these techniques have proved unsatisfactory in many applications for many reasons. Passive techniques usually imply a significant mass increase, do not work well at low frequencies and due to the "coupled" nature of the problem it is difficult to predict their effect except in the simplest of applications. For naval vessels, the very low frequency radiated noise signatures have gained increased importance, and passive technologies are solidly confronted with several practical limitations. One approach that has the potential to overcome these difficulties is active control. While active acoustic control was originally proposed in 1933 by Professor Paul Leug in Germany [2] it has only recently re-emerged as a very promising technique to reduce radiated sound fields [3 and 4]. The main reason for this has been advances in high speed data acquisition and processing enabling active control to be done in "real-time". Most practical and frequent active acoustic applications have been restricted to simple one dimensional air duct noise propagation problems. The traditional active approach to the problem of reducing sound radiation from structures is to use several secondary acoustic control sources arranged around the structural noise source. This technique can be seen to have several disadvantages [5]. From an implementation point of view, it is often impracticable to have secondary acoustic sources located away from the structure (as well as error microphones or hydrophones), and this is particularly true for underwater acoustic applications. More important, the use of acoustic control sources leads to a generation of additional unwanted noise, termed "control spillover". This situation is overcome by using additional strategically positioned acoustic sources. Thus, for example, a machine radiating noise requires many active acoustic sources arranged around it to produce global noise reduction (here global means throughout an extended volume or space).

A more recent extension of the active control method has been the introduction of "intelligent" structures or systems with integrated actuators, sensors under the direction of a learning controller [6]. Work in this area has steadily made progress leading to very compact configurations using a multitude of very small actuators and sensors to control many degrees of freedom and collectively a high level of control.

VPI&SU has a long history of accomplishments in acoustics, active structural control and intelligent materials and structures that is internationally recognized, and its engineering graduates have gone

on to be leaders in these fields as well. Structural acoustics is one of the many applications of these technologies that VPI&SU has focused upon with significant successes. As this report illustrates, VPI&SU has a team of expertise that continues to pursue the advancement of active structural acoustics for U. S. Navy objectives.

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3.0 ACTIVE STRUCTURAL ACOUSTIC CONTROL OVERVIEW

The purpose of this research is related to a technique in which the noise radiated from vibrating structures is reduced by active inputs applied directly to the structure itself. The active inputs may take the form of oscillating forces or strains, adaptive steady state forces or adaptive changes in material properties. While the control inputs are applied directly to the structure, the error information (i.e., the variable to be minimized) has previously been taken from the radiated acoustic field, but an important innovation is using structural sensing to provide pressure related information. The subtlety of this approach is that one can take advantage of the nature of the behavior of the structural acoustic coupling to optimize and reduce the dimensionality of the controller. This discipline thus involves the study of the interaction of controller-structure-acoustics. As the aim of the work is to develop structures with embedded or bonded actuators and sensors and develop "intelligent" control approaches, the work falls into the domain of what is called "adaptive," "active," or "smart" structures.

The rapidly emerging field of adaptive structures and the early work that stimulated it, is well summarized in the review article by Wada et al [7]. Figure 2, which was based on Ref. 7, shows a general framework for adaptive structures. The two most basic systems are the sensory structures in which only information related to the states or parameters of the structure are measured. Adaptive structures are those that include actuators that can alter the system states or parameters in a controllable way. The interaction of these two areas is defined by Wada et al [7] as "controlled structures," and thus includes some degree of control intelligence in dictating the required inputs to the actuators to achieve the required sensed states or parameters. A finer definition on controlled structures is "active structures" in which the actuators and sensors are highly integrated into the structure itself. Because the sensors and actuators are directly part of the structure (bonded or embedded) one may then view the structure itself adapting its properties in an active way to a disturbance. Finally, when the control elements and electronics and perhaps even power sources are directly integrated into the structure itself, the structure is defined to be "intelligent" in that it appears to provide its own support energy and cognitive ability (although it admittedly had to be "taught" its process at one stage). For a detailed discussion of the foundation work in sensors, actuators, and applications the reader is referred to Ref. 7.

In terms of controlling sound radiation from structures using active or adaptive means applied directly to the structure while sensing some state or parameter of the structural acoustic system has been demonstrated. Fuller and Jones [8] and Jones and Fuller [9] showed both experimentally and analytically that sound transmission into a model elastic fuselage can be globally controlled with a few point force control inputs applied to the structure. This early work [8, and 9] defined the basis of the initial research in the previous Grant; while the control inputs are applied to the structure the error information was taken from the acoustic field (or structural motions that acoustically radiate) and thus the controlled system includes the natural coupling between the structural response and the acoustic field. This approach was shown, for low frequency applications, to markedly reduce the size (i. e., number of channels) of the controller.

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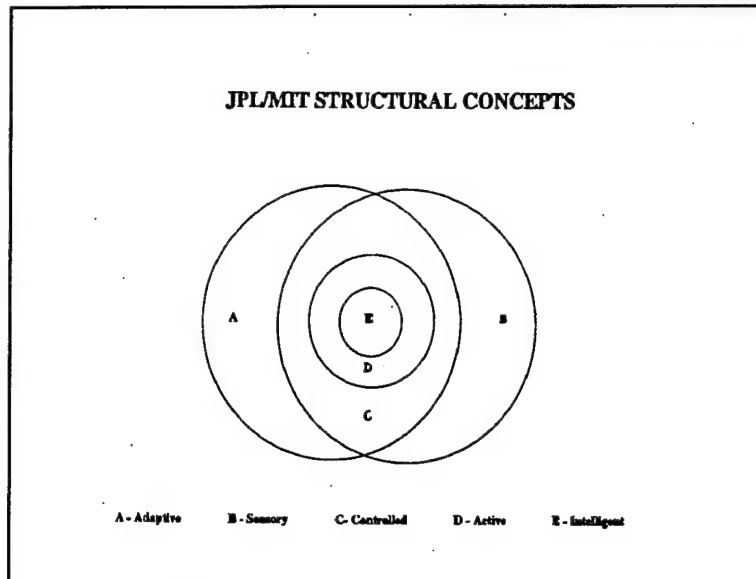
Figure 2 Relationship of smart structural systems.

An important development in the previous work was the initial use of structural sensors rather than farfield microphones for error sensing which is particularly important for naval applications [10]. Discrete accelerometers, and distributed sensors were used to provide an estimate of the acoustic farfield.   The key challenge is appropriate structural sensor processing to minimize the farfield acoustic pressure that does not necessarily reduce the structural vibration.

This previous research further demonstrated theoretically and experimentally the need for developing optimal design techniques to achieve practical and efficient active structural acoustic control systems. This includes the design and placement of actuators and sensors, and control algorithms. With optimization significant acoustic control can be achieved with fewer actuators and sensors that greatly simplifies the control system.

The following sections will detail VPI&SU's continuing progress in active structural control techniques, and the technologies developed for their implementation. For clarity, the discussion is divided into the four areas; structural acoustics, actuators, sensors and control approaches. However, the research is always a complete synthesis of the above four areas due to the "coupled" nature of the problem. For brevity this report is limited to a discussion of the concepts and highlights; details of the experiments or analyses can be found in the appropriate references, bibliography, and papers included in Appendix C (separate enclosure). The authors believe that this report defines a rapidly evolving field in noise control that has an important role in advanced naval vessel and other vehicle designs, aerospace, and industrial applications.

4.0 STRUCTURAL ACOUSTICS

Structural acoustics is directly concerned with the coupling between the motions of elastic structures and their radiating (or receiving) sound fields. The response of these systems must be solved simultaneously (or in a coupled sense) as in heavy fluids or highly reactive environments the back loading (radiation impedance) of the acoustic field affects the motion of the radiating structure [1]. Obviously this natural "feedback" loop has important implications on the design of active systems for such situations. This section will discuss some important characteristics of structural acoustic coupling and how they relate to the present problem and VPI&SU most recent contributions to the field.

In previous VPI&SU ASAC research the number and position of actuators were varied to determine the effects of control authority using multiple actuators and sensors [11]. Experiments using a simply supported plate with PZT (Lead Zirconate Titanate) actuators using the "Filtered-X" version of the Widrow-Hoff adaptive controller with microphone sensors showed the importance of actuator location for the control of acoustic radiation. Thus actuator placement optimization approaches were further developed as well [12].

Wavenumber domain approaches for active control were initially investigated analytically and experimentally [13] under the previous Grant and have been continued here. For the plate used in preceding experiment, taking the 2-D wavenumber transform of the plate-baffle system one can show that modal suppression corresponds to a general fall in the amplitude of plate response across the complete wavenumber spectrum. However, for modal restructuring there is a reduction in supersonic (propagating) wavenumber components and an increase in subsonic (nonpropagating) components [14]. As discussed in Ref. 1, for planar and cylindrical structures only supersonic wavenumber components radiate to the far-field, and thus although the averaged panel response is approximately the same or possibly greater, the radiated far-field sound levels fall globally.

Control cost function implementations based upon wavenumber domain objectives were addressed, and suggested that sensors can be shaped to observe only the supersonic wavenumber components can yield a minimization of the acoustic structural response [14]. Global minimization of total radiated power from a plate for would require a 2-D integral evaluated over the spatial wavenumber region -k to +k.

Another interesting observation is that, using a stationary phase approach to evaluate sound radiation from panels, it can be shown that only one spectral wavenumber component of the complete structural motion will lead to radiation toward one particular spatial angle [13]. Thus, if one designs an optimal controller to minimize particular isolated wavenumber components on the structure, sound radiation can be minimized at the corresponding radiation angle, without the use of an error microphone in the radiation far field.

Under this Grant VPI&SU has further refined and expanded the development of active structural acoustic control and addressed many of the issues raised in the preceding research. These

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developments demonstrate a considerable advancement in the understanding of active structural acoustics and the procedures for more optimal acoustic designs. The following paragraphs will highlight this work.
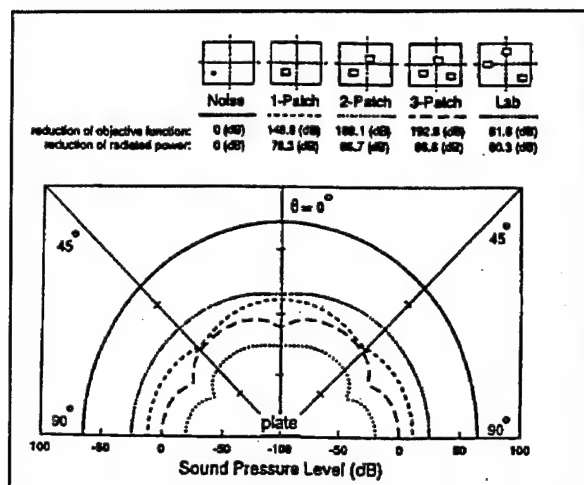
4.1 OPTIMAL ACTUATOR/SENSOR PLACEMENT

In the period of the previous Grant, algorithms were developed and evaluated for choosing optimal actuator/sensor configurations for controlling sound radiation from baffled simply supported plates [12 and 15]. The resulting acoustic responses predicted from analytical models were compared to experimental results obtained from appropriate measurements in the VPI&SU anechoic chamber. The results clearly demonstrated the significance of the optimization.

Initial investigations were applied to optimize the location of a rectangular piezoelectric actuator and both the size and location of a rectangular surface strain error sensor constructed from PolyVinyliDene Fluoride (PVDF). The single optimally located actuator results were further compared to those from control with a non-optimally positioned actuator as well as and multiple control actuators. In addition, either microphones are used to provide error information in the test cases or a single optimally located and dimensioned PVDF error sensor was implemented as the cost function. Results from these studies indicated that optimization of control actuators and error sensors provides a method rivaling in importance the performance increases gained when acoustic control is achieved with microphone error sensors and increasing the number of control actuators.

Development of another optimization approach using Linear Quadratic Optimal Control Theory (LQOCT) continued under this Grant. With this approach, the optimal design parameters for the multiple actuators can be constrained to meet physical limitations such as plate boundaries and limitations on control voltage to the actuators and the availability of specific sizes of the material. Also, the simultaneous optimization of actuators and PVDF sensors were performed [12]. Most recently it has been applied to the optimal placement of multiple fixed size piezoelectric actuators combined with the feedforward LMS control algorithm using a selected number of microphones to represent the global system response [16]. It has demonstrated that optimization can lead to a reduction in the number of actuators required. Figure 3 shows representative results in terms of the acoustic and plate vibration patterns. The results show that off-resonance optimization of actuators leads to a significant performance improvement over a randomly selected arrangement (denoted "lab"). In general optimization of transducers was shown to be of the same order of magnitude of importance as increasing the number of channels of control (i.e., actuators and sensors).

Many numerical optimization approaches such as discussed in the previous paragraph have practical limitations that make them unsuitable for complex structures or systems with large number of actuators. By formulating the feedforward control approach as a multiple regression problem, it is possible to instead use subset selection to find the best actuator locations to give the best system performance [17 and 18]. This new technique is general enough for use on complex structures that cannot be modeled analytically, and it is efficient enough to allow comprehensive studies involving large numbers of actuators. There is an analogue between multiple linear regression and feedforward

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control which aids in understanding the control problem. The analogue for feedforward control is
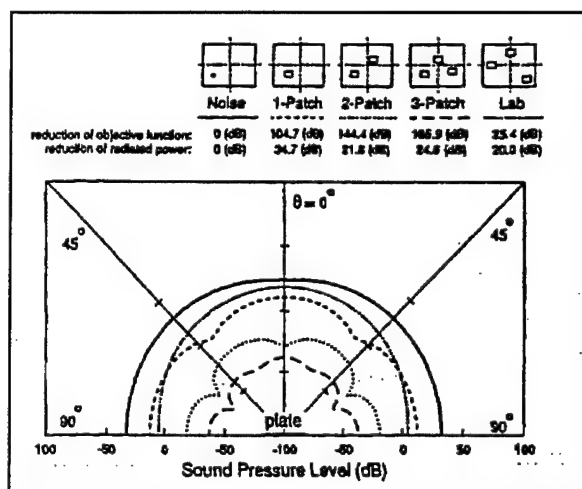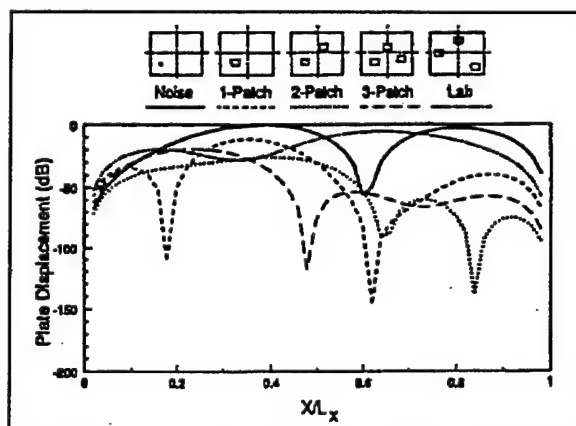

a. Radiation pattern for f = 357 Hz.
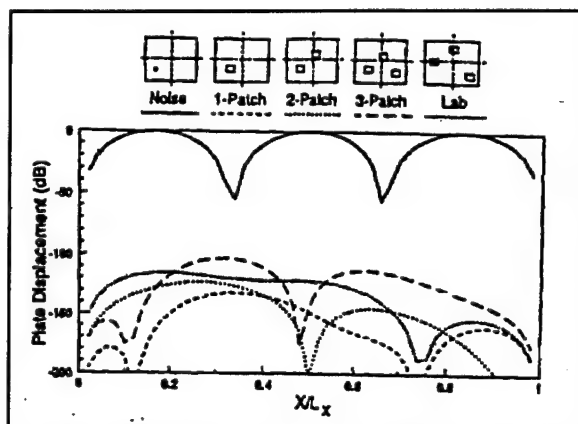
b. Plate displacement for f = 367 Hz.

c. Radiation pattern for f = 272 Hz.

d. Plate displacement for f = 272 Hz.

Figure 3. Measurements for optimal placement of actuators.

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that the actuator to error sensor responses are the predictor variables, the control forces are the regression coefficients, the desired response is the model, and finally the dependent variable equals the negative of the disturbance. Since the method is based on discretized transfer functions, it is quite general and is ideal for simulations involving numerical models and experimental data.

Statisticians have developed the concept of subset selection or variable reduction that can be used here since there are so many variables to be dealt with [19 and 20]. The method used here is the exhaustive search method. Since it is not practical nor desirable to optimally chose from a full set of a large number of actuators, subset selection lets us choose an optimal subset of actuator locations from among the many candidates, in effect optimizing their locations for the given disturbance and frequency.

The technique has been demonstrated using numerical simulation for a simple system in which the radiation from a cylindrical shell is controlled by oscillating forces applied to the shell surface [18]. A particular example is a finite-length, fluid-loaded cylindrical shell with rigid (i.e., pinned) flat end caps as shown in Figure 4a. The disturbance is an oscillating distribution of axial ring forces as shown in Figure 4a as well. The candidate actuators, shown in Figure 4b, are axisymmetric ring-forces acting normal to the shell surface at evenly spaced locations along the cylinder's length. Figure 4c shows the disturbance of normal surface velocity due to the disturbance force. Response of the system is modeled using the NASHUA FEM/BEM program [21] whose formulation solves the fully coupled structural-acoustic response. In feedforward control we assume the disturbance force response alone is known at the sensor locations. The design objective is to drive the actuators so as minimize the total radiated power.

The best subsets of four or fewer actuators are examined at a frequency of ka=0.59, where k is the structural wavenumber and a is the shell radius. The best subsets of one, two, three, or four optimally located actuators will provide the radiated noise reduction as shown in Figure 4d. The horizontal axis shows the rank among subsets. Reductions range from 12 dB with one actuator to over 70 dB with four actuators. Figure 4e shows the actuator locations for the 15 best of each size set. The horizontal axis shows where the actuator is located along the cylinder. Each row on the chart represents a different subset, with actuator locations appearing as squares in the appropriate location. The reduction in radiated power for each subset is shown in decibels at the left side. The best subset is shown in the top row, second-best in the second, etc.

Subset selection provides an efficient, versatile, general way to optimize actuator locations. However, the analyst must be sure to test the results for collinearity, the numerical ill-conditioning that can result from poor choice of actuator locations. The collinearity problem has also been addressed in this research. The more complicated the physical system is, the more important it is to have formal, general methods for optimizing the system configuration.

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a) Geometery of example problem.

b) Locations of candidate actuators.

c) Operating shape at a=0.59

d) Reductions in radiated power.

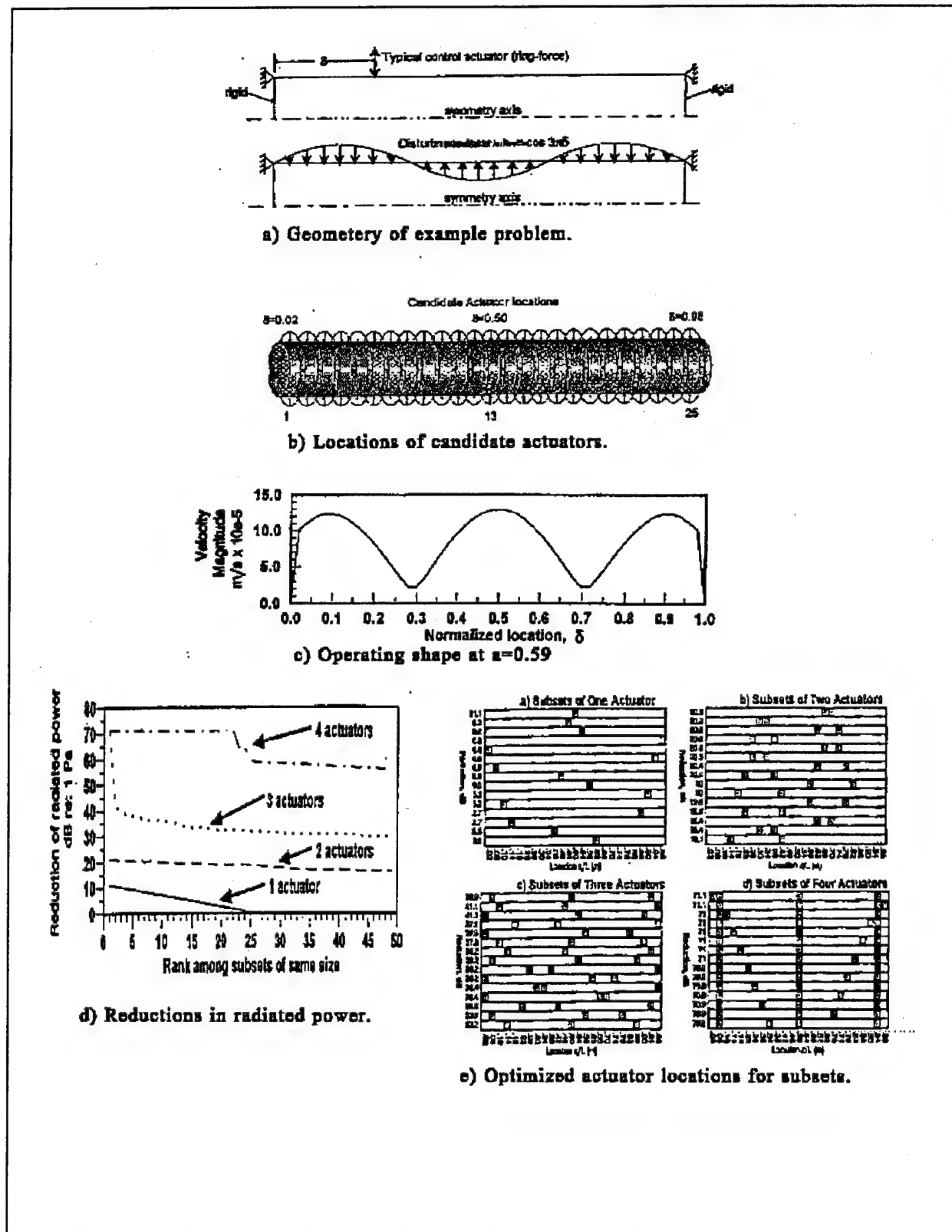e) Optimized actuator locations for subsets.

Figure 4 Example problem for optimum actuator locations using subset selection.

Optimization of actuator locations for multiple-frequency excitation has been addressed for the acoustic radiation from a simply supported rectangular plate [22]. The developed procedure used non-linear optimization techniques for the optimal location of piezoelectric actuator(s) by using radiated acoustic sound power as the objective function. In addition, it is shown that the optimization approach provides a method to design a robust controller with respect to the frequency uncertainty for single-tone excitation cases.

Broadband optimization of integrated actuator and sensor locations has been experimentally demonstrated for controlling acoustic radiation from a simply supported plate [23]. The experiment was designed with up to three control PZT actuators, and three PVDF or microphone sensors over a bandwidth of 0 to 400 Hz. Actuator and PVDF sensor locations were designed using the preceding optimization approach [22] to simultaneously minimize the total sound radiated power at a number of excitation frequencies. Two separate experimental plate configurations were required where Figure 5 is for the SISO and 2I2O cases, and Figure 6 for the 3I3O case. The actuators are labeled with an A#, and sensors labeled with an S#. A broadband (i.e., 0-400 Hz) disturbance signal was applied to the plates with a single shaker at the location illustrated that excited the five natural modes of plate vibrations. The SISO and 2I2O cases were optimized for the plate (1,1) and (3,1) mode frequencies (the most efficient radiating plate modes), and for the 3I3O case the optimization was for the (1,1), (2,1) and (1,2) mode frequencies. Details of the 3I3O digital controller are discussed in Section 7.2.2.
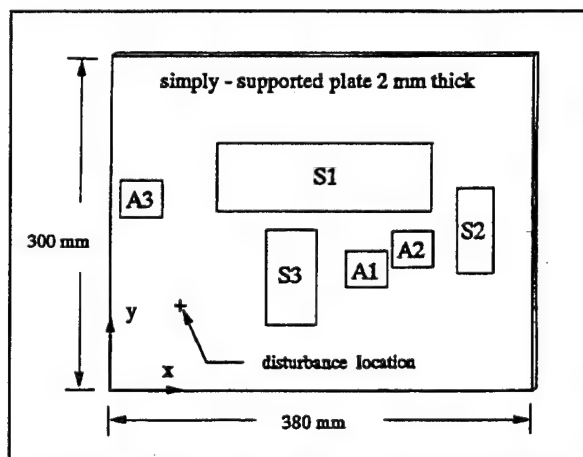
Figure 5 Actuator and sensor locations for Plate 1.
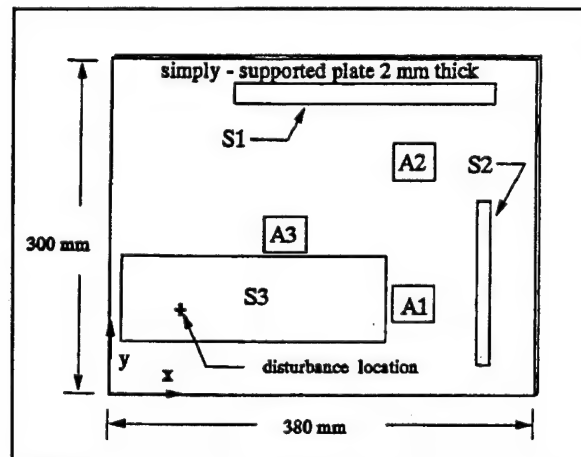
Figure 6 Actuator and sensor locations for Plate 2.

Farfield results as a function of angle for using microphones as error sensors are presented in Figure 7 for the plate natural frequencies, and the total radiation directivity results are shown in Figure 8. The sound spectrum for an error microphone at 30 degrees is shown in Figure 9. For the cases of using of using the PVDF sensors similar results are shown in Figure 10 to 12.

Experimental results show limited reduction in farfield acoustic radiation for a SISO configuration. This is because the SISO controller is unable to observe and control all radiating plate modes over the frequency band. When the controller configuration was extended to 2I2O, an average sound reduction of 11 dB at all directions was obtained. Further extension of the controller configuration to 3I3O provided only an average 1 dB improvement. The results for microphones and PVDF error sensors produced similar results. These result is the first to demonstrate broadband radiation control with an "adaptive" structure, i.e., integrated actuators and sensors.

Figure 7 Radiation directivity at (a) 86 Hz, (b) 182 Hz, (c) 248 Hz and (d) 331 Hz using microphones ——— No control, -.-.- SISO, ... 2I2O, ----- 3I3O.

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Figure 8 Total radiation directivity using microphones as error sensors
_____ No control, -.-.- SISO, ... 2I2O, ----- 3I3O.

Figure 9 Spectra of error microphone at -30° for 3I3O
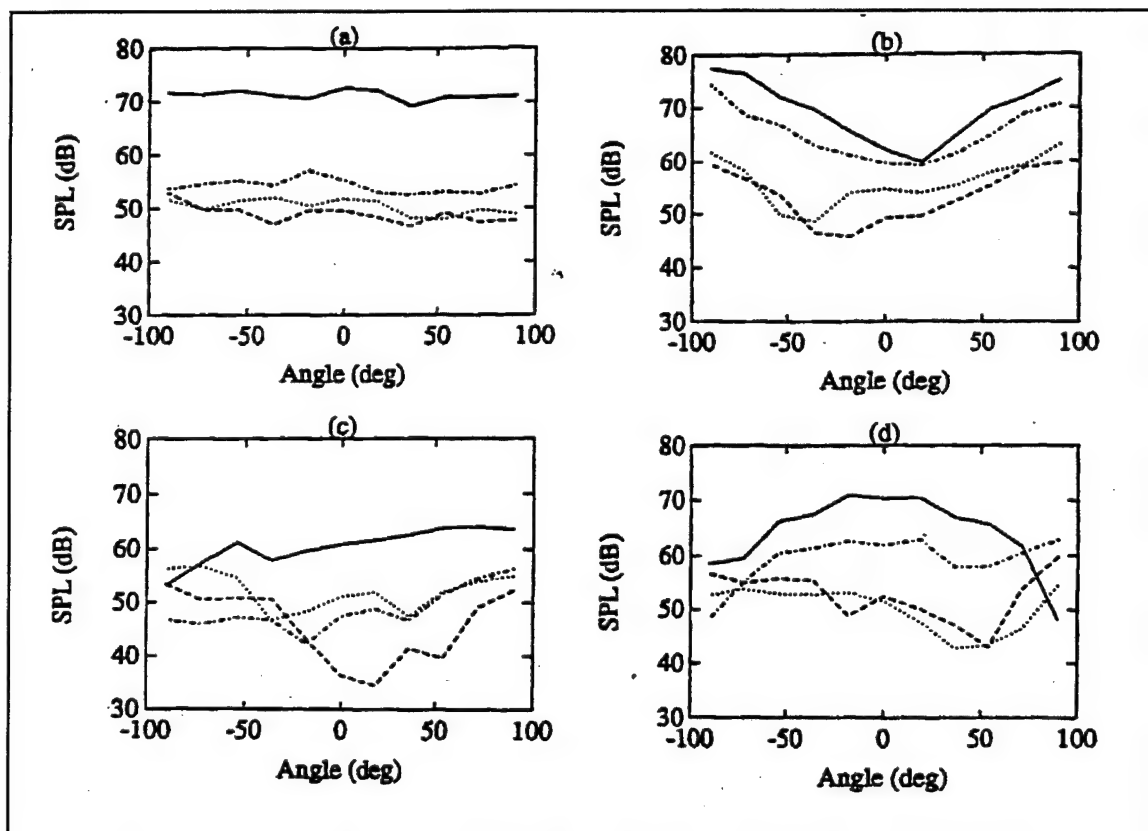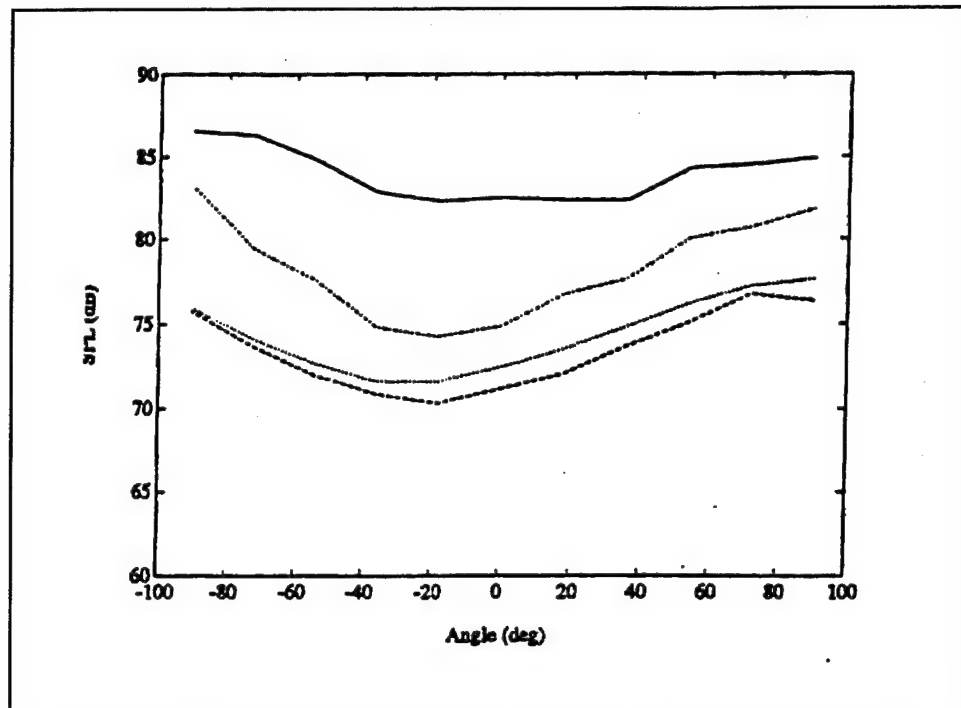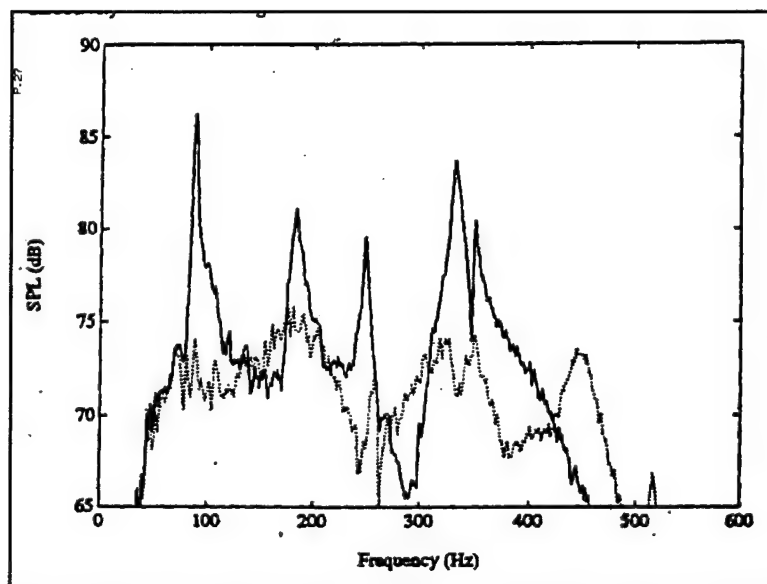control system. _____ before control, ... after control

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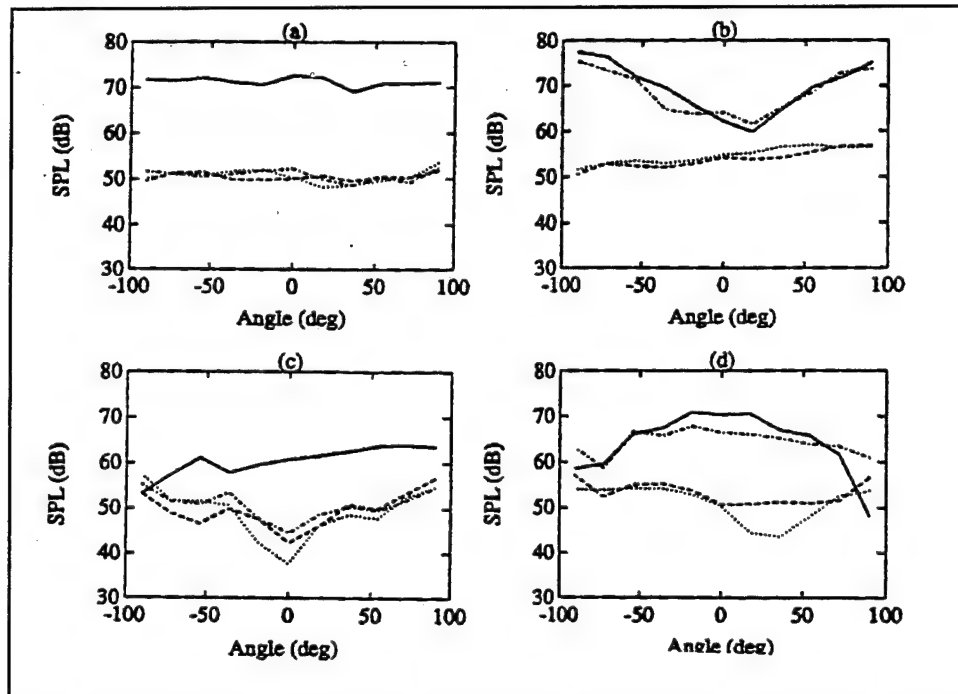
Figure 10 Radiation directivity at (a) 86 Hz, (b) 182 Hz, (c) 248 Hz and (d) 331 Hz using PVDF sensors.
———— No control, -.-.- SISO, ... 2I2O, ----- 3I3O.
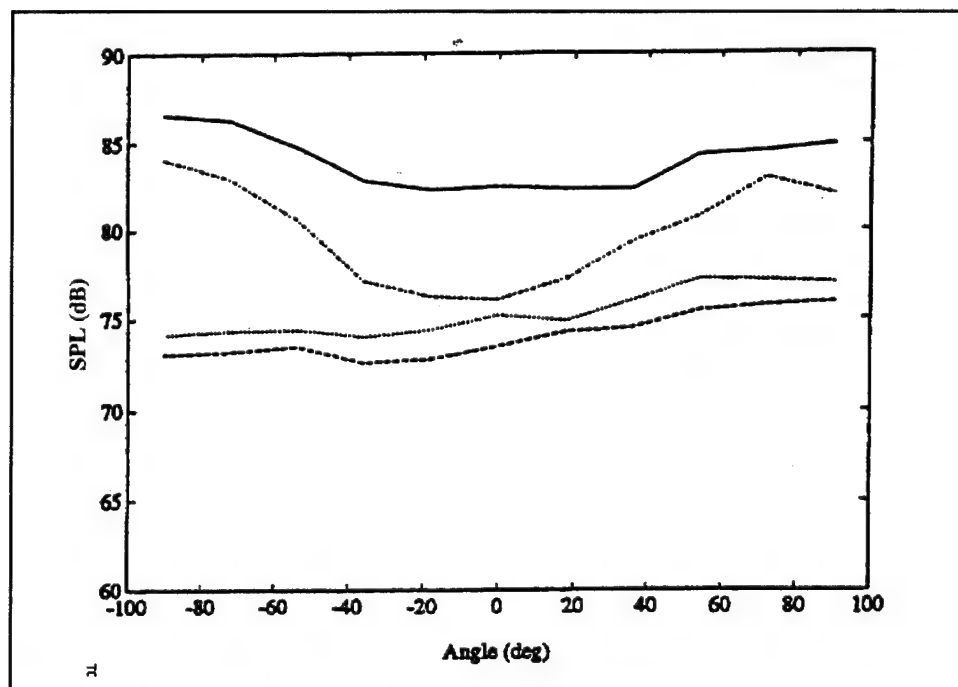
Figure 11 Total SPL radiation directivity using PVDF as error sensors
———— No control, -.-.- SISO, ... 2I2O, ----- 3I3O.

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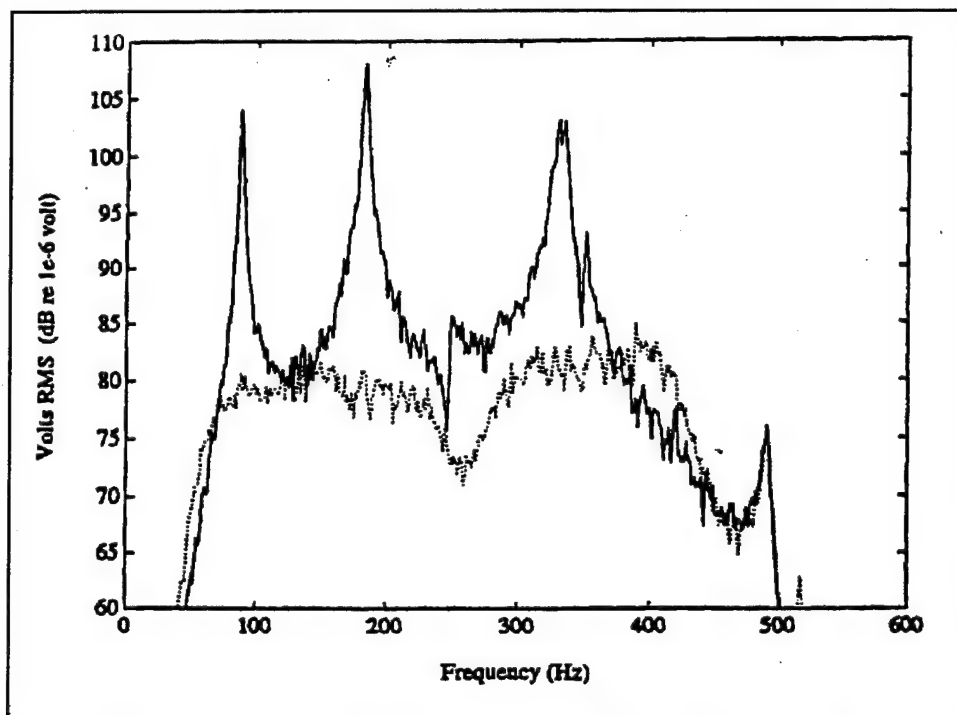
Figure 12 Spectra of error PVDF error sensor P2 for 3I3O control system.
_____ before control, ... after control

VPI&SU has additionally investigated the optimum selection and placement of actuators and sensors for structural acoustic control applications based on eigenfunction assignment. Modification of the eigenstructure can be such that the system responds to the weakest set of modal radiators [24]. This technique is applicable to both narrowband and broadband radiation problems. It has been experimentally demonstrated for controlling the acoustic radiation from a plate using a single channel adaptive LMS feedforward controller. The optimum actuator sensor configuration resulted in excellent global sound reduction. Eigenanalysis approaches are further discussed in Sections 4.3.

4.2 WAVENUMBER DOMAIN

Wavenumber domain based approaches have continued to be developed under this Grant both analytically and experimentally. The control objective here is to reduce the supersonic (propagating) wavenumber components that radiate to the far-field. Under the previous Grant the work addressed control cost function implementations based upon wavenumber domain objectives, and demonstrated that wavenumber analysis of structural vibrations proves to be a powerful alternative tool for studying the mechanisms of control [13]. Wavenumber domain experiments were performed using simply supported beams, 2-D baffled plates, and shaped sensors.

New work has been concerned with developing (analytical and experimental) structural sensors and associated signal processing techniques that provide time domain estimates of farfield pressure and

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wavenumber information over a large bandwidth. This work has advanced to real-time sensing and control experiments, and is currently being extended to address cylindrical radiators.

4.2.1 REAL TIME WAVENUMBER SENSING

To reduce control authority and complexity for minimizing sound radiation structural acoustic sensing should filter out the non-radiating components of the structural vibrations. In the work of this project [26, 27, and 28] a set of point structural sensors (accelerometers) with an array of Finite Impulse Response (FIR) filters and associated signal processing have been used to estimate the supersonic wavenumber components coupled to acoustic radiation in prescribed direction(s) over a broad frequency range. This approach has progressed experimentally from doing real-time control experiments with simply supported beams and to real-time multiple-input-multiple-output (MIMO) control for plates. Additionally, this work has been paralleled with extensive analytical and simulation studies.

The accelerometer outputs are passed through FIR filters and summed to provide far-field radiation information. The filtered and summed time domain signal(s) can be used directly as the error information in a control algorithm such as the single or multidimensional configurations of the Filtered-X version of the Widow-Hoff LMS time domain algorithm. For controlling a plate using 3-input-3-output (three channels) an experimental controller a system was implemented using a TMS320C30 digital signal processor. Figure 13 illustrates the plate experimental setup with nine discrete accelerometer sensors and three piezoelectric patch type actuators. The disturbance signal is applied at a single location on the plate as shown using a shaker.

Experimental results for controlling plate radiation were obtained with wavenumber sensors designed to provide estimates in the horizontal directions of $\theta = -36°$, $\theta = 0°$, $\theta = 36°$, and with error microphones located in the farfield at the same angles. Error microphone outputs can be used as error signals for comparison purposes. Figure 14 shows the experimentally measured auto-spectrum of the third wavenumber error signal ($\theta = 36°$) for the controlled and uncontrolled cases, and significant reductions can be seen across the entire bandwidth. Over the range of 10 to 600 Hz the integrated reductions of 12 dB, 12.8 dB, and 13.5 dB were achieved for the three wavenumber error signals. Similarly, using the three error microphones as inputs to the controller the error signals were reduced 9.3 dB, 10.4 dB, and 12.6 dB. The overall performance for the two control approaches is better illustrated by Figure 15 that shows the reduction in decibels integrated over the 10-600 Hz bandwidth and measured in the horizontal plane. The three dashed-dotted radial lines show the three directions of minimization. Wavenumber sensing over a large bandwidth clearly yields the same levels of attenuation as error microphones in the farfield.

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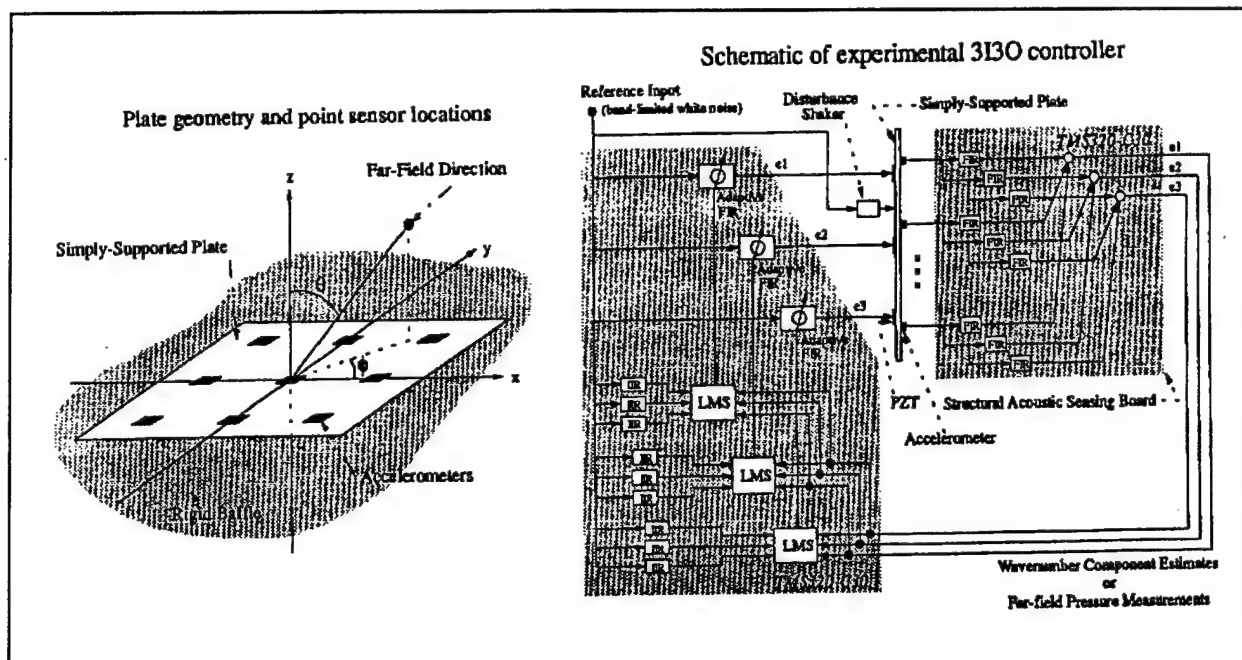
Figure 13 Plate configuration for real-time ASAC control with structural sensing.
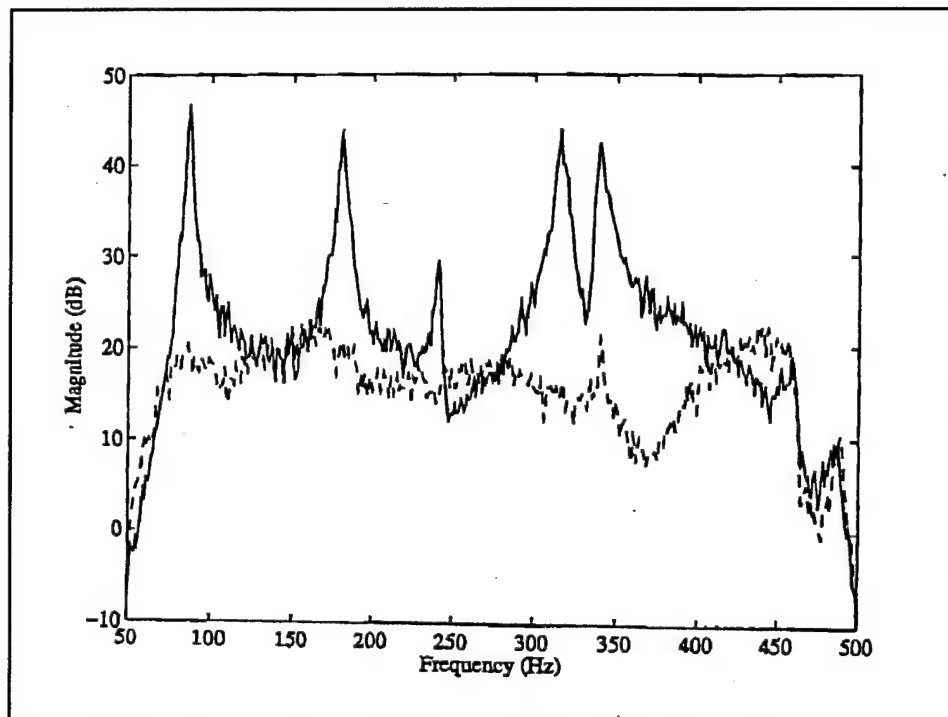
Figure 14 Measured auto-spectrum of the third wavenumber error signal
($\theta = 36°$) for the controlled (- - - -) and uncontrolled cases (------).

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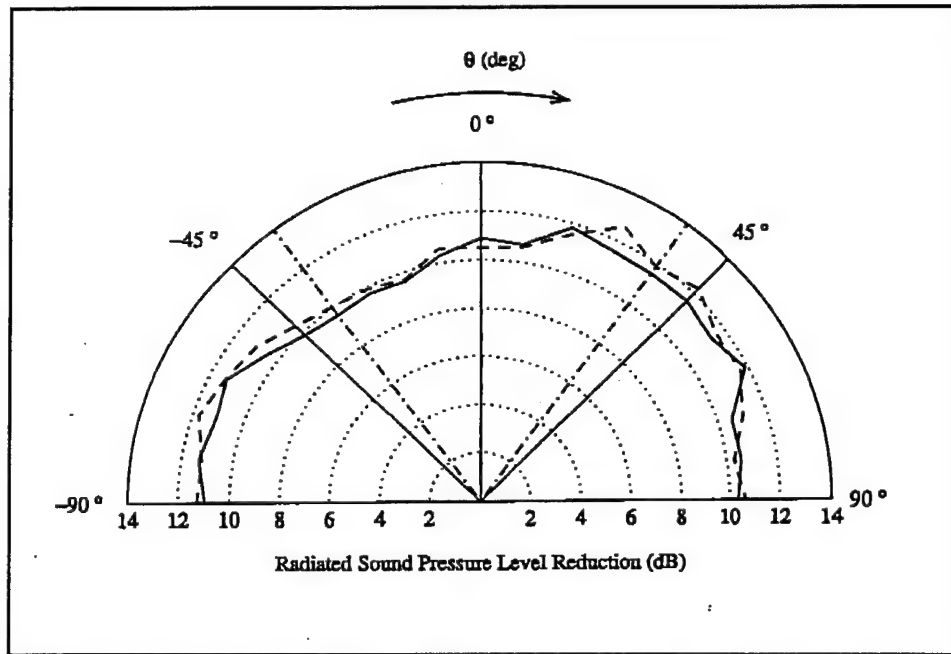
Figure 15 Reduction in decibels integrated over the 10-600 Hz bandwidth and measured in the horizontal plane.

4.2.2 NON-REGULAR SAMPLING TO REDUCE ALIASING

Aliasing is always present up to a certain degree when using point sensors. The structural vibration wavenumber spectrum of any finite length system extends to infinity. Therefore, components above the Nyquist wavenumber will aliase. Important aliasing errors will occur in the Discrete Wavenumber Transform if strong wavenumber components in the structural response are located above the Nyquist wave number. When applied to sound radiation, wavenumber sensing needs only to be accurate within the supersonic region. One way aliasing can be reduced is by filtering out the subsonic region using for example spatial filtering which can be implemented using shaped distributed sensors. With point sensors, it is necessary to alter the response of the sensor array using non-regular sampling [29]. An optimal non-regular spacing scheme can be found that minimizes the error between the continuous and discrete wavenumber transform evaluated over the subsonic region for a number of frequencies. Figure 16 shows an example non-regular optimization result versus the ideal and regular sampling cases and the resulting sensor locations. Non-regular spacing has greatly improved the accuracy of estimation of the supersonic region compared to the regular sampling approach without having to add sensors.

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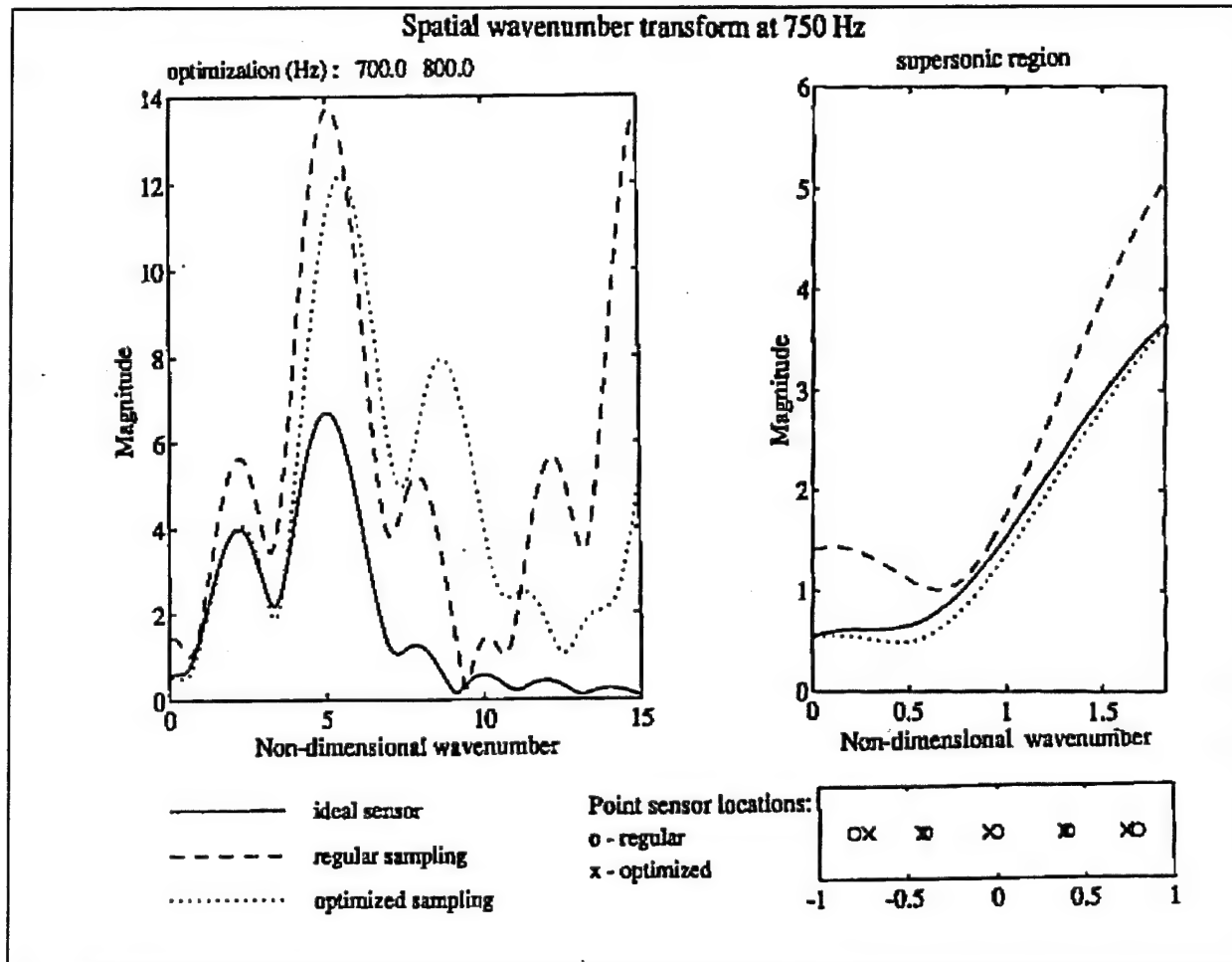
Figure 16 Real-time structural sensing with non-regular sampling.

4.3 EIGENANALYSIS APPROACHES

This research effort has addressed the dynamic characteristics of feedforward controlled elastic systems, and continues to develop approaches to predict the dynamic characteristics of controlled structural vibration and acoustic systems [24 and 25]. It has been shown that the controlled system effectively behaves as having new eigenproperties. Controlled eigenvalues and eigenfunctions depend on the control force and error sensor locations, and independent of the input disturbance. The applicability of this formulation has been extended to the development of design procedures and methods for active structural acoustic control systems such that they have desired characteristics. The technique is based on the modification of the eigenstructure such that the system responds with weakest set of modal radiators. This technique is applicable to both narrowband and broadband disturbances. This design approach has been verified experimentally for beam and plate structures. The method has been extended to address more complex structures such as cylinders using numerical techniques such as FEM/BEM and to consider broadband excitation. The method provides a basis

by which feedforward controlled systems can be designed for specific requirements in contrast to the largely "ad hoc" methods frequently used. This approach has further been verified by experiments

4.4 NASHUA NUMERICAL MODEL

Active structural acoustic control has been demonstrated in the literature for several elementary structures using analytical models. However, analytical approaches cannot be easily used for the practical and important case of a three-dimensional structure immersed in a dense fluid, which occurs primarily in marine applications. Such fully coupled problems, in which appreciable fluid-structure interaction takes place, require a numerical approach. Submerged shells are of significant practical interest, and for a general, three dimensional fluid loaded shell no such analytical expressions exist. The research initiated for the previous Grant and continued here uses a numerical approach to develop a general algorithm for investigating active structural acoustic control of submerged structures [30]. Predictions of the dynamic response and radiated noise field were obtained using the computer program NASHUA developed by Everstine [21]. VPI&SU is cooperating with the Carderock Division, Naval Surface Warfare Center, Bethesda, Maryland to extent the capabilities and applications of the NASHUA model. NASHUA uses the finite-element program NASTRAN to compute structural quantities, and a boundary-element formulation to solve for the fully coupled structural acoustic response. There are two significant advantages to using an approach based on NASHUA. First, no discretization of the ambient fluid is required since the fluid is modeled using boundary elements. Second, the approach can be used for any structure that can be modeled using NASHUA.

The control algorithm used is a feedforward method in which require *a priori* knowledge of the nature of the disturbance. After specifying the number and locations of the control actuators, Linear Quadratic Optimal Control Theory (LQOCT) is used to solve for the complex optimal actuator forces that minimize a quadratic cost function.

The method is illustrated using a thin, fluid loaded spherical shell for which there are analytical solutions for certain excitation types. The results here only address steady-state, single frequency forcing functions, and to further simplify the analysis only forces applied in a global plane are considered. This simple case serves as a benchmark with which to develop methodologies and computer programs in anticipation of more complex structures. The closed form solution also serves to validate the numerical results. For the normal point force excitation, there exists an analytical solution for the dynamic responses of a thin spherical shell as presented by Junger and Feit [1]. The results for a single force as a function of frequency agree well throughout the frequency range in predicting the radiated power, the control forces, and the residual responses as compared to the analytical solution.

Controller performance can depend strongly on both the number of actuators and their locations, and the control algorithm developed can easily handle multiple control forces. In addition to examining the effects of actuator locations, the approach can be used to optimize the actuator locations and also the control forces vs. frequency.

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The application and evaluation of the NASHUA model have been extended to address multiple actuator control. For the thin walled shell a relatively small number of control forces are required to achieve global reductions in radiation at low frequencies ($k_o a < 1.7$). A single point force actuator reduces the radiated power due to a point force excitation by up to 20 dB at resonance frequencies. Between resonance frequencies more actuators are required because of modal spillover. With multiple actuators radiation can be reduced by 6-20 dB over the frequency range $0 < k_o a < 1.7$. The NASHUA model was also used in the previous analysis of Section 4.1 for the optimization of control forces on a fluid loaded cylinder.

4.5 CAPPED FINITE CYLINDER

While most active structural acoustic control experiments are done with beams or plates VPI&SU has accomplished more complex experiments with cylindrical structures [31]. In one set of experiments a long thin aluminum cylinder (1.28 x 0.254 m, and 2.77 mm thick) was configured with two rigid end caps (27.5 mm thick) and instrumented with 36 piezoceramic actuators arranged in three rings about the circumference and with PVDF structural sensors in two separate configurations. The controller used a narrowband Filtered-X LMS algorithm implemented on a TMS320C30 DSP chip for the control of up to six channels. The input disturbance to the cylinder was generated with a shaker attached by a stinger, and all tests were done in the VPI&SU anechoic chamber. In the first series of tests, the cylinder was excited in the first longitudinal mode with a shaker attached to the end cap. Upon applying control and using three PVDF sensors configured for sensing the first longitudinal mode, significant levels of global sound attenuation, approximately 25 dB on-resonance and 15 dB off-resonance, were observed in the acoustic field. In both the on- and off resonance test cases three control actuators were required to achieve these attenuation levels due to the interaction of the longitudinal and cylindrical modes. In the second series of tests the cylinder was driven radially with a shaker to excite the higher order cylindrical modes. Control was applied with six piezoceramic actuators wired to control selected circumferential modes in the first case, and the actuators were chosen in a helical pattern about the cylinder in the second test case. In the latter case, approximately 10 dB of global sound attenuation was observed in the acoustic field using microphone error sensors, while results obtained using the six PVDF error sensors (configured for the cylinder modes) yielded little sound attenuation in controlling the cylindrical modes. Measurements of the cylinder's surface velocity were also obtained from a scanning laser vibrometer to support the analysis.

The significant levels of control for the fundamental longitudinal mode were primarily due to the large separation in frequency between the modes. The cylinder modes are more difficult to control due the much larger number of modes involved, and the PVDF modal sensors proved to be less effective.

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5.0 ACTUATORS

Early active structural acoustic control investigations used point force actuators as control transducers. There are disadvantages of such devices, mainly that they are cumbersome and require some form of restraining back support or large reaction mass. In view of these limitations, much work has been carried out by VPI&SU to develop actuators bonded to or embedded in the structure itself. Under the previous Grant VPI&SU investigated piezoceramic, PolyVinyliDene Fluoride (PVDF), and shape memory alloy (SMA) actuator technologies for active structural acoustic applications.

Analytical work showed that piezoceramics can be bonded to the structure surface and used to excite selected modes of vibration [32]. The piezoceramics can be tailored in shape and location to selectively excite certain modes of vibration. This has the advantage of reducing control spillover into unwanted structural or acoustic response. Classical laminated plate theory (CLPT) [33] was applied to a laminated plate with induced strain actuators, such as piezoceramic patches [34]. This research included the development of closed-form solutions of the induced strain field from piezoelectric actuation.

VPI&SU investigated the development of distributed PVDF structural acoustic actuators for structures that are curved where it would be difficult or impractical to employ piezoceramic patches for one or more reasons. Most of the continuing work with PVDF under this Grant has focused on sensor technologies, and is more extensively discussed in the sensor section of this report.

Other work concerned the use of shape memory alloys (SMA) as adaptive inputs. They provide a very compact, light weight, and highly reliable means of actuation, but the response times are relatively slow since it is a thermal process. The main aim of the work was the development of adaptive structures using embedded shape memory alloys. The applications of such "smart" structures are many [35] and much work was carried out to derive the fundamental equations of motion and behavior for such structures and materials [36]. In contrast to the piezoceramic transducer, the active input is not oscillating and what is really being developed was a truly adaptive (or smart) structure whose properties and response can be altered by electrical inputs. Thus, this actuator implementation represents a semi-active control approach.

This section reports on VPI&SU continued development of actuator technologies for active structural acoustic applications. Most of the focus is on the use of piezoelectric ceramics that have proven highly effective and most successful.

5.1 PIEZOCERAMIC ACTUATORS

Piezoceramic actuators are noted for very high force and low displacement outputs, and simplicity in use. The most noted ceramic is Lead Zirconate Titanate (PZT), but the number of piezoelectric materials available is rapidly expanding. The U.S. Navy continues to sponsor most of the basic material research for sonar transducers and hydrophones, and more recently for active control

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applications. These unique ceramics are available in a variety of forms as stacks, sheets, laminates, and bimorphs, and with different directional sensitivities. They are attractive for high frequency applications where small displacements are effective.

VPI&SU has considerable experience in the application of piezoceramic actuators to active control of composite structures. This research program has developed a "generalized laminated plate theory" including induced strain, adhesive layers, and a "conservation of strain energy" analysis scheme for a laminate theory that includes spatially distributed induced strain actuators. These investigations have included the effects of adhesive layer thickness and stiffness on actuation authority. Most of the adaptive structure experimental work to date has dealt with the attachment (i.e., bonding) of PZT type actuators, but theoretical studies have been done to gain a better understanding of the structural dynamic implications of embedding actuators.

5.1.1 DISCRETE ACTUATOR ATTACHMENT METHOD

VPI&SU has made significant progress toward enhancing the design of induced strain actuation methods. With bonded or embedded actuators used for induced structural flexure, the developed in-plane force contributes indirectly through a locally generated moment. Control authority is thus limited by the actuator offset distance. A new concept [37] of flexural control has been developed whereby induced strain actuators such as piezoelectric ceramic patches or shape memory alloys are attached to a structure at discrete points as opposed to being bonded or embedded as shown in Figure 17. This configuration is different from the bonded actuator configuration in two ways. One, because the actuator and the structure are free to deform independently, the in-plane force of the actuator can result in an additional moment on the structure and enhanced control. Second, the actuator can be offset from the structure without an increase in the flexural stiffness of the basic structure. This allows for the optimization of the offset distance to maximize control. Enhanced control is demonstrated by comparing the static response of a discretely attached actuator cantilever beam system with its bonded counterpart systems. The advantages of this system have been verified experimentally, and representative results are shown in Figure 18. The increase in actuator authority achieved by offsetting the actuator depends on the beam-actuator thickness and modulus ratio. For thicker or high modulus substrates, optimal increase in the actuator offset distance results in a substantial increase in flexural control. For the experimental results shown a 40% increase in displacements over the bonded configuration is observed. This attachment method presented is just one of many possible configurations, and a whole array of new geometric and kinematic possibilities is opened.

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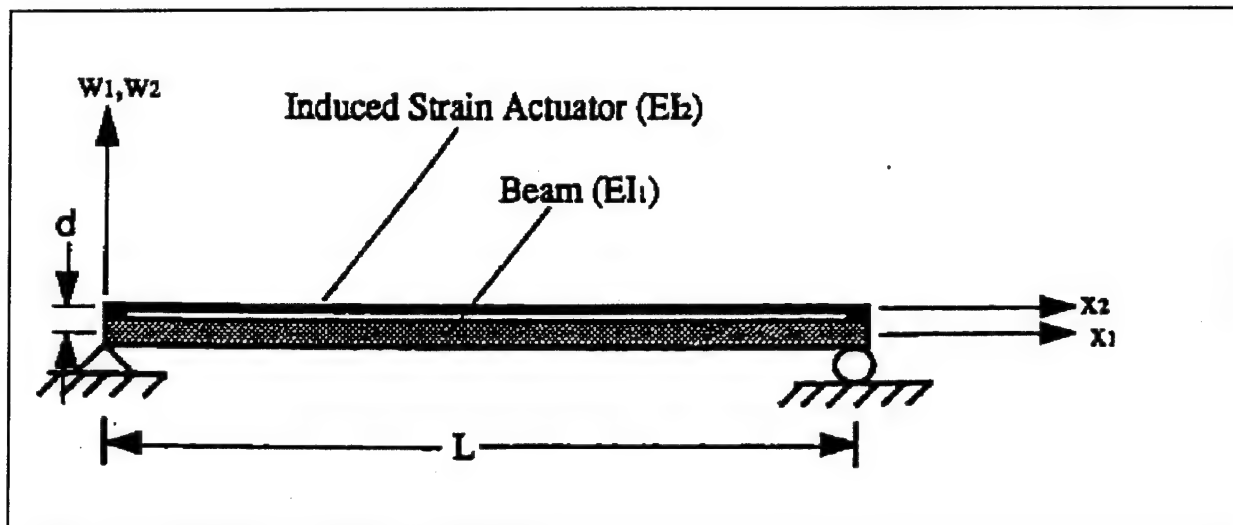
Figure 17 Geometry of attached actuator.
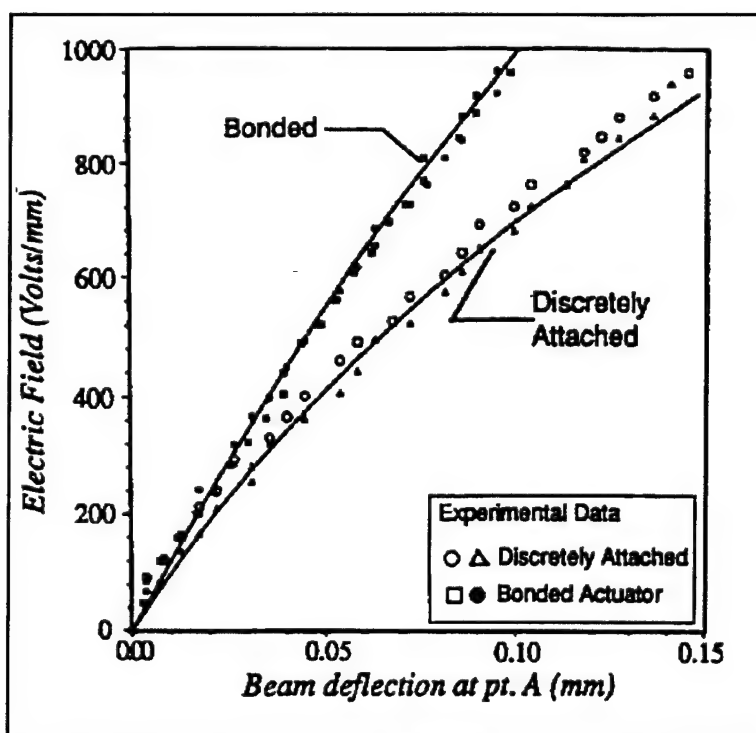
Figure 18 Cantilevered beam deflection test results.

5.1.2 INDUCED STRAIN ACTUATION OF SHELL STRUCTURES

Most of the previous research work on induced strain actuation has dealt with beams and plates, and simple and efficient models have been developed for piezoelectric actuators in particular. However, much less research has been done for modeling the actuation of structures with curvature. Under this Grant progress has been made in modeling the actuation of this important type structure [38 and 39]. An analytical deformation model of a piezoelectrically-actuated circular ring, which takes into account the non-collinear equivalent line forces has been developed. To verify the deformation model, finite element analysis was done. A perfect match between the in-phase actuation deformation model and finite element results, when the actuator mass and stiffness are neglected, thus validating the model.

With an initial assumption that only tangential forces act on the shell structure, as shown in Figure 19, a case of non-equilibrium will exist with rigid body forces. A more proper model is to consider equalizing forces as shown in Figure 20 to counter the rigid body forces for a surface bonded actuator. The proposed self-equalizing modeled radial and tangential displacements are shown in Figure 21 that agree with a finite element model with possible discrepancies due to actuator stiffness effects, thus giving a more accurate model of the actuator.
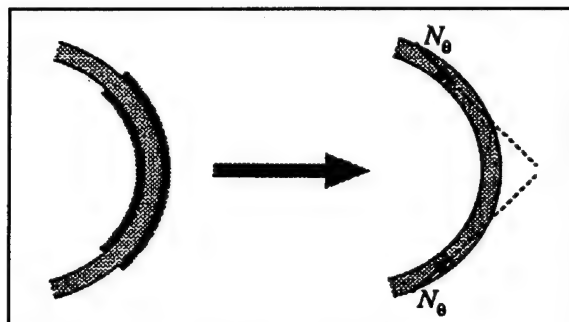
Figure 19 Non-equilibrium of discrete tangential forces in shell structures.
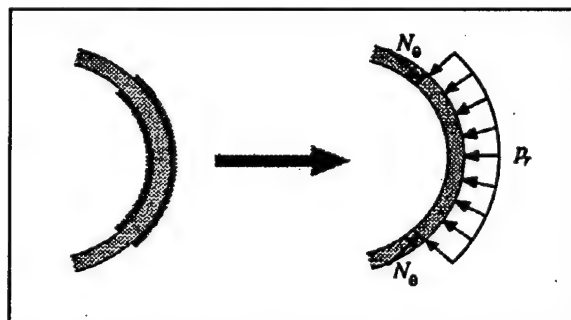
Figure 20 Adequate equivalent loading to maintain equilibrium.

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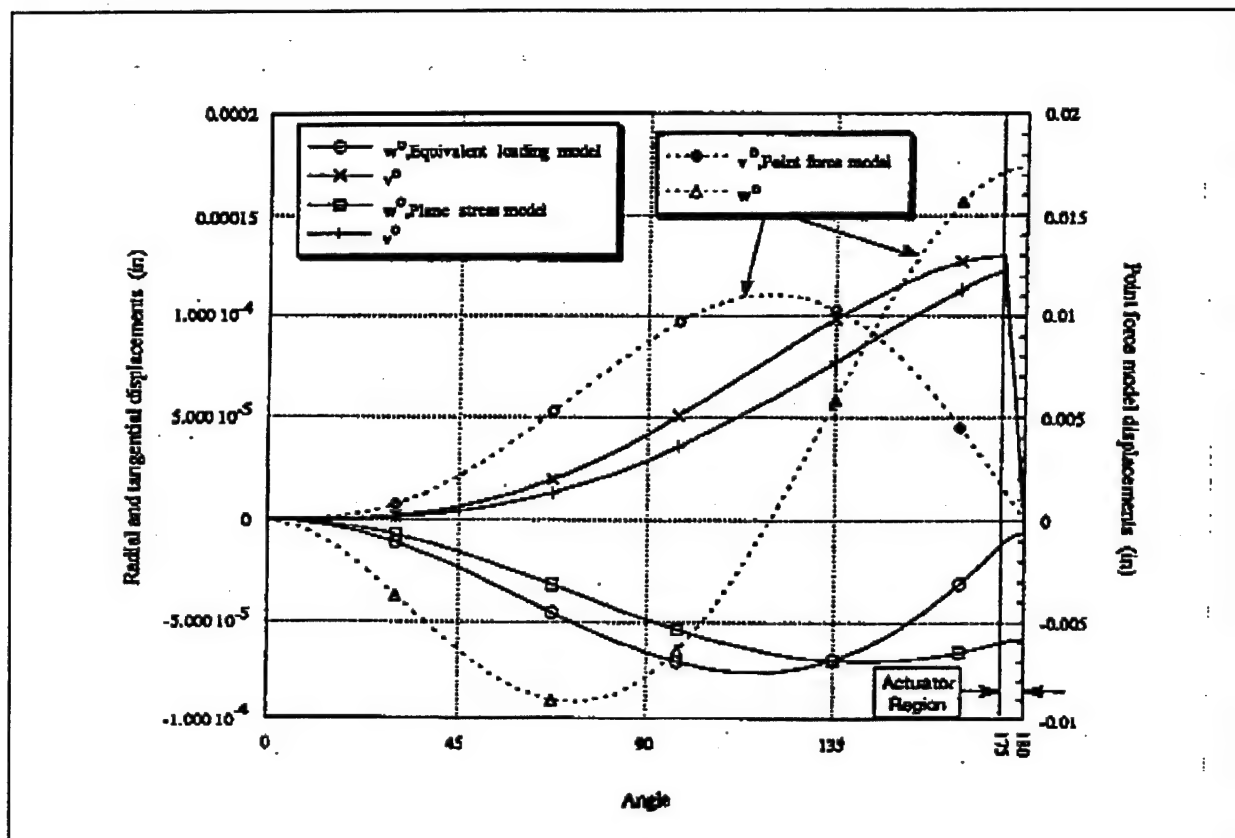
Figure 21 Comparison of the displacements predicted by the proposed self-equilibrating equivalent forces, the plane stress finite element model and the tangential forces alone (no pressure).

5.1.3 DYNAMIC IMPEDANCE ANALYSIS

An active structure is one in which the sensors and/or actuators are highly integrated into the structure itself, such as embedded or bonded. A key aspect is that the behavior and characteristics of the actuators can be altered by the host structure, in particular by its input impedance. There are two approaches currently used in the dynamic analysis of active material systems, one is referred to as the static approach and the other is dynamic finite element approach. Both approaches have some drawbacks in analyzing the dynamic response of active material systems resulting from activation of integrated induced strain actuators, such as PZT patches. New approaches have been developed [40, 41, and 42] to analyzing the dynamic response of active material systems with integrated induced strain actuators, including piezoelectric, electrostrictive, and magnetostrictive actuators. This approach, referred to as the impedance method, has many advantages compared with the conventional static approach and the dynamic finite element approach, such as pin force models and consistent beam and plate models. The impedance of an actuator is understood to mean the electrical impedance measured at its electrical terminals. The impedance serves three purposes: (1) It provides information for impedance matching between the actuator and the electronic drive source. (2) It is used for

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determining actuator efficiency and driving voltage from current responses (or vice versa). (3) It is analytically used to study actuator performance. It is measured electrically, but it depends on the mechanical and driven media (i.e., structure and acoustic radiation) characteristics of the actuator. Mechanical mass, stiffness or compliance, and resistance are in terms of electrical impedances through the electro-mechanical coupling characteristic of the actuator. The effects of the driven medium appear as well in terms of electrical impedance characteristics since they affect the actuator. Impedance is defined as $Z = R + jX = 1 / (G + jB)$ where R is resistance, X is reactance, G is conductance, and B is susceptance

The impedance approach has demonstrated its ability to capture the physics of adaptive material systems, which is the impedance match between various active components and host structures. Further, this approach can be easily used in the electro-mechanical analysis of an adaptive material system to determine the electrical parameters, such as actuator power consumption, system energy transfer and system power requirement. Its utility and importance have been demonstrated by means of experimental and numerical results for a simple example of a PZT actuator-driven one-degree-of-freedom spring-mass-damper system as illustrated in Figure 22. The stress field within a PZT actuator, including the thermal stress resulting from the heat dissipation, can be accurately calculated using the impedance approach. It can be further used to examine the transient electro-mechanical response of the system and structure. The methodology can be used with any actuators, and material systems, and any structures as long as the structural impedance corresponding to the actuator loading and the dynamic characteristics of the actuators can be determined.
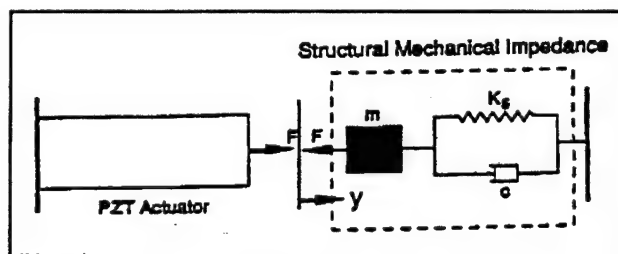
Figure 22 A PZT actuator driven one-degree-of-freedom spring-mass-damper system.

This work has further addressed the case of fluid-structural interaction for underwater structures. [43] A one-dimensional model based on structural impedance has been applied to the case of a simply supported beam in an infinite baffle with fluid medium on one side as shown in Figure 23.
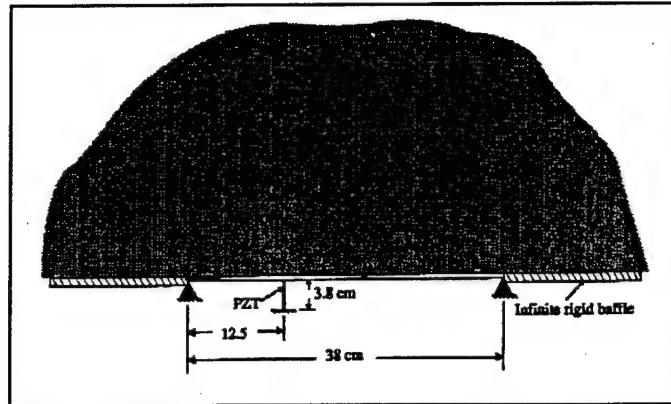
Figure 23 Simply supported baffled beam with vertical PZT support radiating sound into a heavy acoustic fluid on one side.

Power consumption results in air are compared with those in water to illustrate the effect on actuator power consumption and requirements. Figure 24 illustrates the comparison of actuator power consumption for the beam with air and water fluid loading. Water fluid loading has two effects on the structural impedance: the natural frequencies shift to lower values due to the mass loading effects of the water that is more dense than air, and the water creates a two to three orders of magnitude increase in the real part of the off-resonance impedance over the case of air loading. In the fluid loaded case the breakdown of power consumption by the mechanism of dissipation is shown Figure 25. The analysis included the examination of acoustic radiated power as shown in Figure 26. The application of the impedance method should lead to more efficient actuator-structural systems for active control of acoustic radiation since the partitioning of the energy into all the individual dynamic systems is apparent.
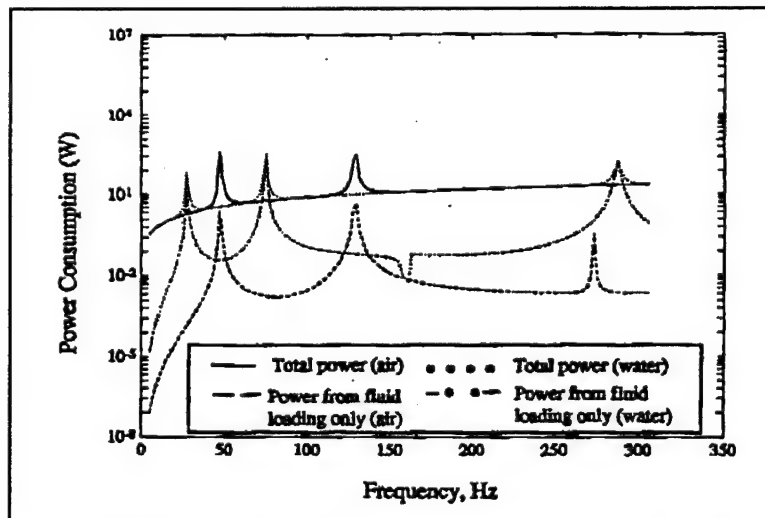
Figure 24 Comparison of actuator power consumption for the beam with air and water loading.

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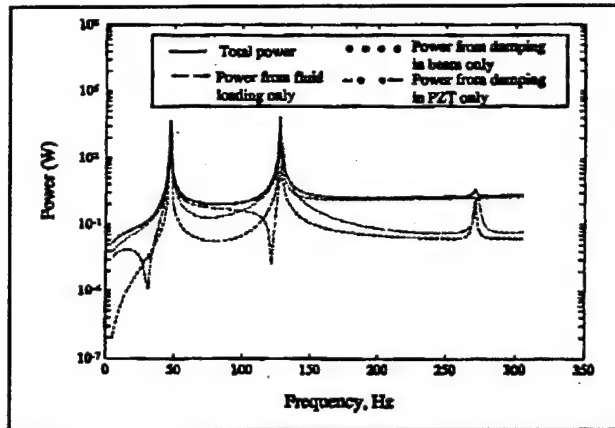
Figure 25 Breakdown of power consumption by mechanism of dissipation.
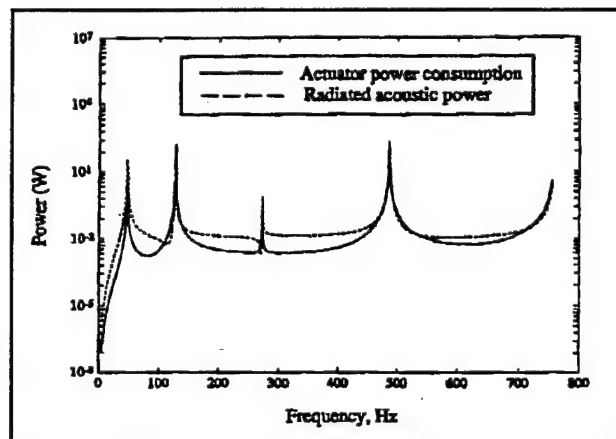
Figure 26 Comparison of power consumption and radiated sound power.

5.1.4 ACTUATOR POWER FACTOR METER

The actuator power factor, defined as the ratio of structural dissipative mechanical power to apparent supplied electrical power, describes the effectiveness of the integrated actuators to convert supplied electrical power that creates the intended structural response [44]. A large actuator power factor in

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the frequency range of application shows that the corresponding actuator (position) has a high authority to excite its host structure in that frequency range than positions with a low power factor. The use of actuator power factor provides an alternative means for the determination of the optimal actuator locations and dimensions to theoretical calculations. What is more important, the power factor can be experimentally measured on large scale complex structures, thereby eliminating the need for sophisticated theoretical modeling. Thus, a power factor meter has been developed as illustrated in Figure 27, and experimentally demonstrated. A functional diagram of the power factor calculation is illustrated in Figure 28.

Figure 27 Schematic of the power factor meter.

Figure 28 Power factor calculation functional diagram.

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6.0 SENSORS

For any control strategy, observability is an important requirement. Thus, sensing of the plant responses to be minimized is an important part of the res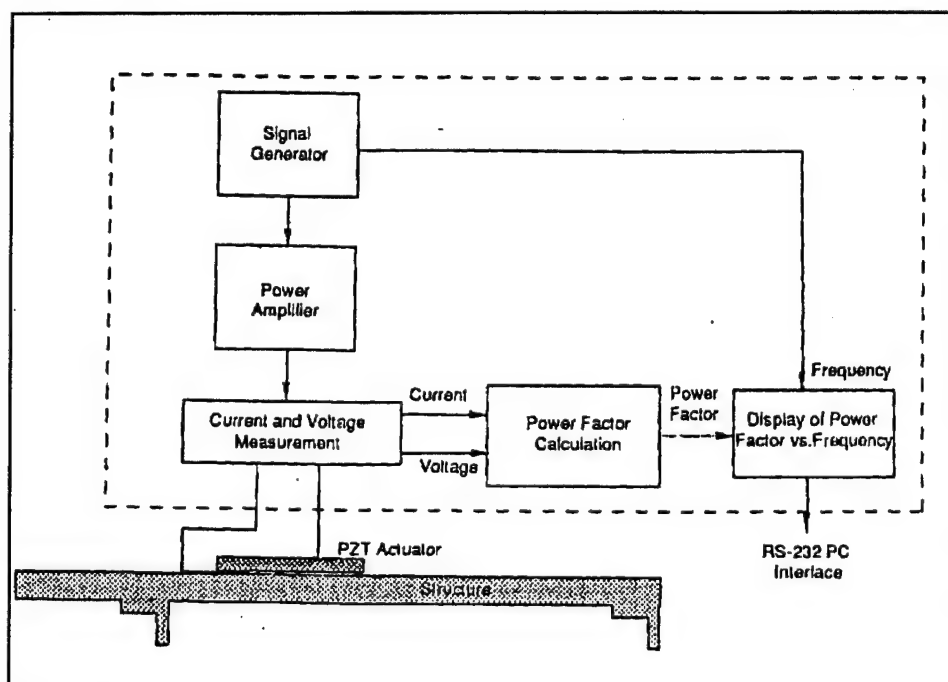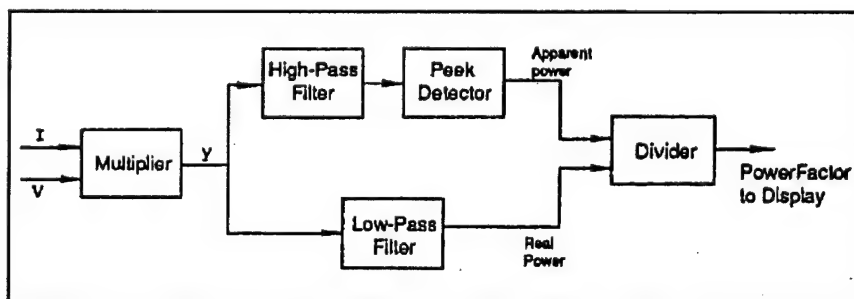earch work described here. In ordinary active structural acoustic control approaches the radiated acoustic field is directly sensed for error information using, for example, microphones. However, there are many situations where such an approach is impractical, particularly for many naval applications. Alternatives have to be sought which is the focus of the continuing sensor developments reported on here.

For the previous research Grant several candidate sensor types were explored that included fiber optic, Nitinol fiber, piezoceramic, and PolyVinyliDene Fluoride (PVDF). VPI&SU demonstrated for the first time active structural acoustic control using optical fiber sensors [45]. The fiber sensors were mounted on a thin, simply-supported baffle plate and configured for most effective detection of the odd-odd plate modes. The experiments were done in the VPI&SU anechoic chamber, and the output from the fiber sensor was used as an error signal. A least mean square (LMS) algorithm was used for digital processing and control was achieved using a single piezoelectric actuator.

Much of the sensor work for this research Grant has concentrated on the continued development and application of piezoceramic and PVDF sensors which show the highest potential and performance for the applications of concern.

6.1 PIEZOCERAMIC SENSORS

Piezoceramic elements were extensively discussed in Section 5.1 as actuators, but they are quite effective as sensors as well. More important, piezoceramic elements can be used for both actuation and sensing when attached to a structure.

6.1.1 COLLOCATED ACTUATOR/SENSOR

A piezoelectric patch may serve as both an actuator and sensor simultaneously because of the piezoelectric effect and its converse. When bonded to a structure and driven by an alternating voltage, it imposes a bending moment on the structure through its longitudinal expansion and contraction, causing the structure to vibrate. This vibration then in turn "modulates" the current flowing to the path. Consequently, the electrical admittance of the bonded patch, defined as the ratio of the current to the voltage, is physically in the same position as its mechanical counterparts, such as compliance and mobility, in representing the transfer characteristics of a structure between the excitation and the response. As a pure electric quantity, the electric admittance is much easier to measure than mechanical transfer functions.

A modal analysis technique has been developed and experimentally demonstrated using collocated sensor-actuator configurations [46 and 47]. The electrical admittance or impedance versus frequency is measured with a sine sweeping impedance analyzer as shown in Figure 29.

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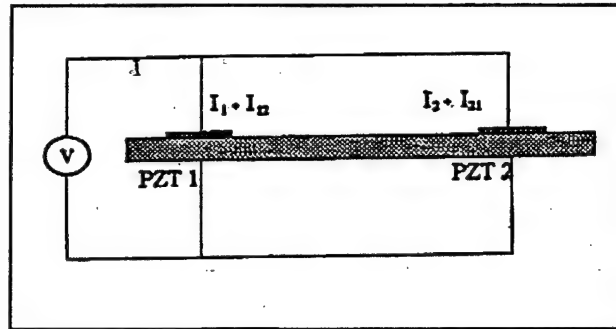
Figure 29 Measurement of transfer admittance between two PZT sensor-actuators.

Two algorithms of modal parameter extraction have been used. One uses electrical admittance match/half-power bandwidth method, and the other employs inverse Nyquist plane curve fitting. Both algorithms can extract a structure's modal damping coefficients, natural frequencies, and curvature mode shapes of the structure. The stiffening effect of the transducers was also considered for small light structures. The method is proven to be effective in conducting modal testing on a structure extremely sensitive to the stiffening of transducers.

A free-free aluminum beam was experimentally used as proof of concept in doing modal analysis. Figure 30 illustrates the sensor-actuator configuration of the beam, and the first four modal shapes extracted (plot (a)). The calculated theoretical mode shapes are shown for comparison purposes (plot(b)).
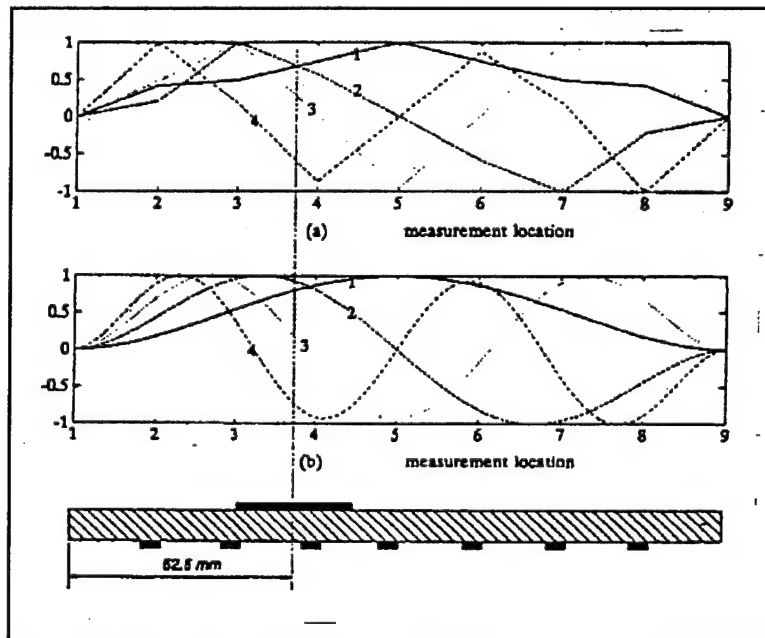
Figure 30 Aluminum beam and related mode shapes.

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Application of collocated sensors/actuators to active structural acoustic control systems directly is discussed in Section 7.1.1 concerning Sensoriactuators

6.2 PVDF SENSORS

Piezoelectric polymers and co-polymers [48] such as PolyVinyliDene Fluoride (PVDF) thin films have gained popularity in recent years in the development of distributed actuators and sensors. Much interest has been given to the piezoelectric properties of these materials as the functionality and development of polymers in recent years has increased. They are compliant, lightweight, tough, plastic films that are available in a variety of sizes, shapes, and thicknesses, and configurations that include bimorphs. It is highly sensitive over a large bandwidth (>1 GHz), but it is noted for not being a highly efficient electro-mechanical transmitter due to its large compliance. An important design issue is the positioning and shaping of these sensors

Reference 12 discusses experimental work where PVDF distributed sensors were directly attached to vibrating panels and used as error sensors in an active structural acoustic control approach. When the PVDF sensors were shaped to only observe the odd-odd modes of the simply supported panel (i.e., the efficiently radiating modes), high global reductions in far-field sound were measured. This result should be contrasted to the use of point structural sensors such as accelerometers, which often lead to an increase in radiated sound levels [49]. In effect the shaped PVDF sensor acts as an analog structural wavenumber filter. If the sensor is long compared to the structure, then the PVDF sensor averages the response of high wavenumber, short wavelength, inputs (subsonic components) to zero while retaining information from the low wavenumber, long wavelength, inputs (supersonic components). As discussed previously a structural error sensor with these characteristics is highly desirable as the controller is only observing the critical radiating components of the motion of the structure. Associated with such approaches is a significant signal processing requirement in which the sensed data is converted into the required control variables.

6.2.1 SHAPED PVDF SENSORS

The use of distributed sensors has recently gained acceptance in the control community for their inherent built in filtering capability of the system response. The flexibility, light weight and toughness properties of PVDF films have found application as distributed structural sensors in active control. Shaped PVDF sensors were previously developed by VPI&SU for active structural acoustic control experiments [50 and 51]. The PVDF sensor is mounted on the structure and yields a response proportional to the integral of the strain over the surface of the application. In particular, one dimensional problems are ideally suited to the use of PVDF distributed sensors because any desired weighted response can be obtained by varying the width and polarity of the sensor as a function of the coordinate.

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In this project a shaped PVDF sensor was designed to be used to demonstrate eigenvalue assignment control for a simply supported beam [52]. The PVDF sensor outline is illustrated in Figure 31, and the outline was defined in terms of modal response error components. In this experiment, the sensor whose output is to be minimized was designed to induce the desired dynamic characteristics of the structure. An experimental test of the sensor of Figure 31 demonstrated that the open loop system eigenvalues could be successfully moved to their assigned values to their assigned values when used in conjunction with a feedforward controller.
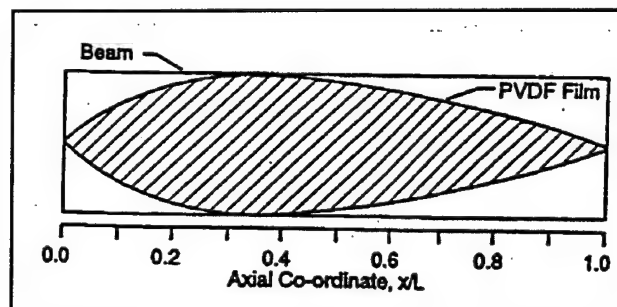
Figure 31 Shaped PVDF sensor outline for error sensing on a beam.

6.2.2 MODAL SENSORS

VPI&SU has further investigated modal sensing of efficient acoustical radiators with PVDF distributed sensors in active structural acoustic control approaches [52], and here it has been extended to address two dimensions simultaneously. The radiation efficiency for several modes of a simply supported plate approaches unity for all modes when the structural wavenumber is greater than the acoustic wavenumber in the surrounding media. When the structural wavenumber is greater than the acoustic wavenumber, the radiation efficiencies for the odd-odd modes (x and y) are the highest. However, the radiation efficiencies of the even-even modes are the lowest, which is of interest in control of sound in this regime, since these modes will not contribute significantly to the radiated field. Only those modes possessing a high radiation efficiency must be observed and attenuated to effectively reduce the far field sound pressure level. In some applications, particularly off-resonance, the response of the panel increases while sound radiation decreases. Because of this observation, the dimensionality of the controller can be greatly reduced.

A control experiment was performed using multiple piezoceramic actuators along with accelerometer and PVDF sensors bonded to a plate. The plate used in this experiment was configured with two sets of piezoelectric actuators as illustrated in Figure 32, and the control approach was based upon the Filtered-X version of the adaptive LMS algorithm implemented in a TMS320C25 DSP processor for two channels of narrowband control. The shape and location of the PVDF sensors are chosen such that the (3,1) mode was dominately observed. A signal generator was used to drive a shaker as the

disturbance source and to provide the reference signal to the controller. The interconnections with the adaptive controller are illustrated in Figure 33. Experiments were done for both on and off-resonance cases of the plates. PVDF modal sensors consistently proved superior to accelerometers in selectively filtering the desired (3,1) mode that is an efficient radiator. This is because distributed sensors are capable of spatial modal filtering, and accelerometers are incapable of performing the same task without post-processing. Note that this work also demonstrates the extension of one-dimensional sensor theory to use on two-dimensional structures.

Fig. 2 System schematic

Figure 32 Plate control experiment configuration for selective modal sensing.

Figure 33 Filtered-X adaptive feedforward controller

Experiments were performed implementing the shaped PVDF modal sensors and accelerometers in active control of plate vibrations. The frequency response between the disturbance force point and sensors was measured with a random input, and Figure 34 shows the comparison of PVDF and predicted results. For the (3,*) modal sensor the maximum response corresponds to the resonant frequency of the (3,1) mode as illustrated in the upper graph of Figure 26, and the results for the (*,1) sensor are shown in the lower part of Figure 34. Then using the two sensors as observers a 2I2O controller will dominately observe and control the (3,1) mode.
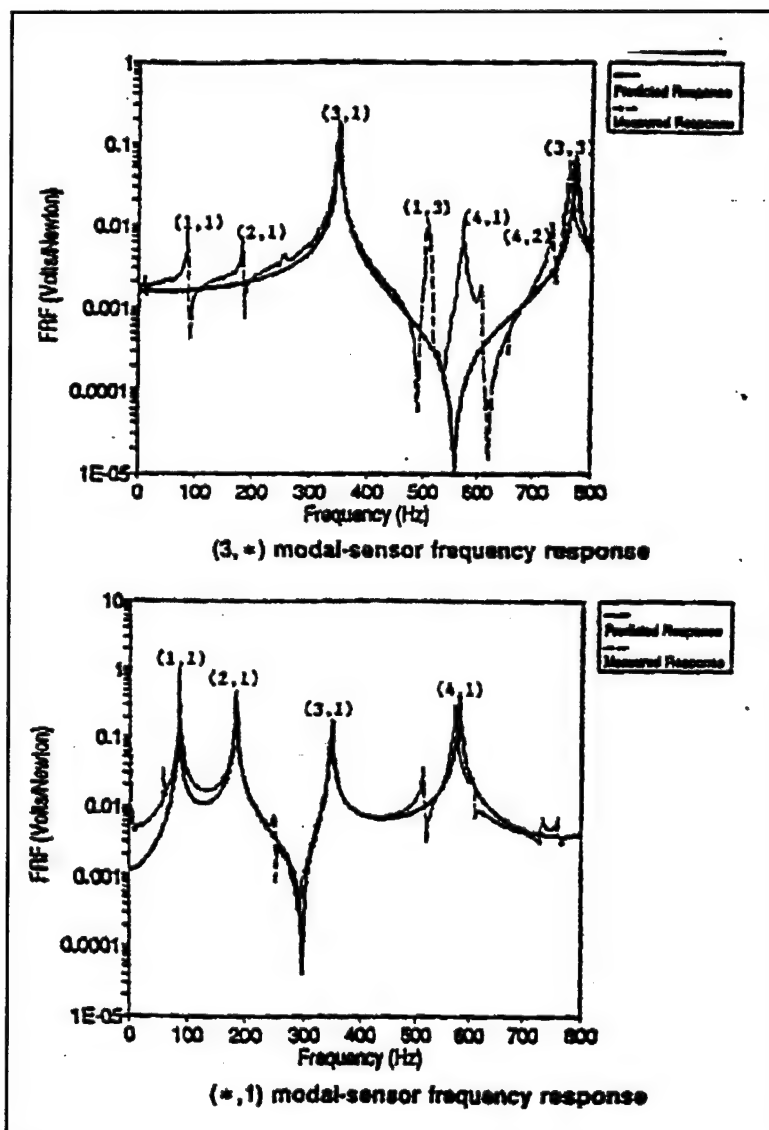
Figure 34 Measured and predicted frequency response functions for the PVDF modal sensors in the x and y directions respectively.

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Active control experimental results for using both PVDF modal and accelerometer sensors are illustrated in Figures 35 as a function of the plate modes. The results are for both on- and off-resonant frequencies. the PVDF modal sensors, and for the accelerometer sensors. These results clearly show the advantages of PVDF modal sensors over accelerometers for both on- and off-resonant frequencies in that the use of the (3,1) PVDF sensor always leads to the largest reduction of the (3,1) mode.
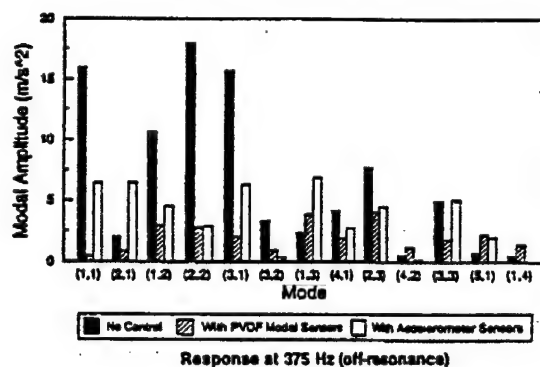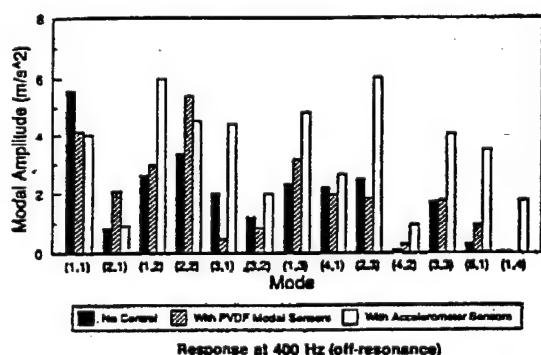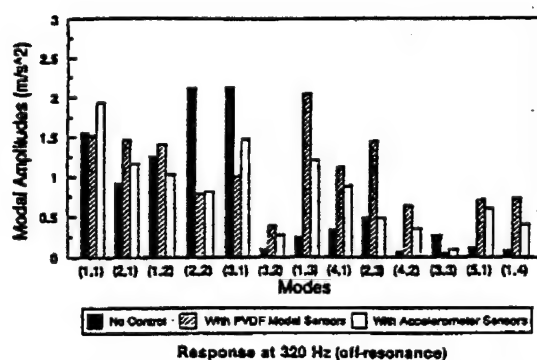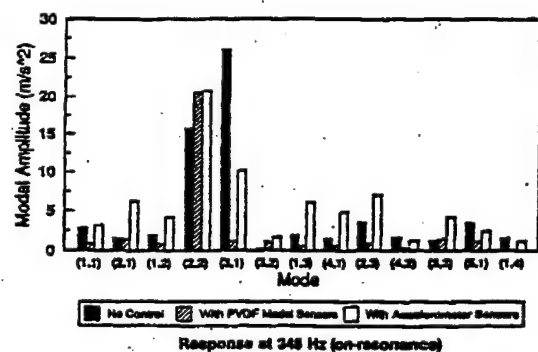
Figure 35 Controlled modal amplitudes.

7.0 ACTIVE CONTROL TECHNIQUES

An important part of active control of sound radiation from structures is the choice, design and implementation of a suitable controller strategy. VPI&SU has continued development, implementation and evaluation of many control approaches under this Grant. The ultimate choice of strategy is highly dependent upon several factors but perhaps the most important is the nature of the noise input, whether it is steady state sinusoidal (including multiple frequencies), random or transient. These investigations have made progress in considering the impact of broadband disturbance characteristics such as controller time delay effects with broadband feedforward and feedback controller designs. All these type noise conditions will be encountered in structural acoustic applications.

Terms such as active control and cancellation of acoustic noise can be easily interchanged and/or misused. To help clarify the meaning of the various active approaches some definitions are in order. "Control" is to optimally attain and maintain a desired (required) state (steady and/or dynamic). "Cancellation" is to null out a state by the superposition of an opposite polarity. Control has the broadest definition, while cancellation is more specific, and should be considered a subset of active control. "Control" does not necessarily have to mean that the acoustic field is reduced in level, but rather it is in a desired form. One example is the control of room or theater acoustic properties such as the reverberation time and spectral emphasis. However, most frequently it implies a minimization through control techniques that could be passive, semi-active, or fully active.

VPI&SU has considerable experience developing control approaches that could be classified as semi-active and fully active techniques for the control of radiated noise. Passive techniques are defined by dissipation based upon material and structural properties, dependent upon only local properties, and can only dissipate and temporarily store energy. However, they are inherently stable, and do not require sensors, actuators, or controllers. Semi-active techniques on the other hand attempt to control with actuators the dissipation of energy using real-time or near real-time control with local or remote sensing. The semi-active control system response can be designed to be tailored to particular disturbance characteristics, and to adapt to changing conditions. Fully active techniques can additionally supply energy and dissipate it, and can be designed to be fully coherent with the disturbance and remotely sensed information.

Research into the application of state feedback methods focused on casting the structural acoustic control problem into the paradigms of modern control theory. In this research, Linear Quadratic (LQ) techniques such as Linear Quadratic Gaussian (LQG), and Linear Quadratic Regulator (LQR) have been investigated theoretically and experimentally. This has included the development of Kalman filter state estimators, and techniques such as H_∞. Continuously persistent narrowband and wideband disturbances were investigated and transients with considerable success experimentally.

For applications in which the noise field is a steady state sinusoidal input (or multiple frequencies) and sometimes random broadband, the feedforward least-mean-squared (LMS) adaptive approach has proved quite successful [53]. Early active acoustic applications of the adaptive LMS algorithm were

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one-dimensional, but it has been extended to multidimensional acoustic fields [54] and structural radiated noise [51]. Another important aspect of the feedforward LMS control approach is that, in general, as contrasted with the optimal approach, it relies on control inputs to the structure that may be viewed as having all the mass, spring, damper parameters of an attached substructure. Thus the controller can be viewed as performing "system modification" to lower the structural response by altering the system input impedance to the noise source [56]. The modified input impedance thus generally results in lower noise energy transmitted into the control field. Previous analytical work has also shown that, analogous to feedback controlled systems, the feedforward controlled system has new eigen properties [56].

7.1 STATE FEEDBACK CONTROL TECHNIQUES

This section presents progress made in the area of conventional control theory approaches to active structural acoustic control system designs.

7.1.1 SENSORIACTUATOR

The development of simultaneous sensing and actuation for a single piezoelectric element, called a sensoriactuator, provides the opportunity for truly collocated control in adaptive structures [57]. A variation on earlier feedback active structural acoustic control methods, direct radiation feedback (DRFB), is suggested for the sensoriactuator. This method relies on a discrete-point formulation of the associated radiation energy norm. The influence of the acoustic dynamics on proven sufficient conditions for globally stable collocated velocity feedback has been addressed for the first time. Selection of an appropriate Lyapunov function for the stability analysis of collocated DRFB is addressed and compared to previous results for direct velocity feedback in active vibration control.

It was concluded that, unlike the vibration energy norm, the radiation energy norm provides a positive definite Lyapunov function but does not exhibit continuously decreasing radiated energy. Specifically, it was not possible to show that the derivative of the Lyapunov function was positive semidefinite. The conclusions are that the radiated energy of the system, as formulated, is not guaranteed to be monotonically decreasing. Physically, this is related to the oscillatory behavior of the function in time. However, it is also intuitive that the radiated energy of the system should exhibit asymptotic stability under certain controller gains. It remains to select an appropriate Lyapunov function to show this stability and this will be a focus of future work.

7.1.2 LQ-MIMO CONTROL LAWS

Multi-Input/Multi-Output (MIMO) control strategies produce improved performance over Single-Input/Multi-Output (SIMO) methods when applied to the Active Vibration Control (AVC) and Active Structural Acoustic Control (ASAC) problems. However, digital MIMO control is limited due to a higher computational load resulting from an increased system order, more control gain calculations, and etc. The decreased sampling rate results in a decrease in controller bandwidth and can affect closed-loop stability criteria (i.e., gain and phase margin). In addition, the observer

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structure can affect both bandwidth and closed-loop stability. The application of digital MIMO control approaches for real structures has been investigated under this Grant [58]. Considerations such as computational load, system model order, and control law complexity were evaluated for a variety of MIMO control methods. Experimental results were obtained for LQR-MIMO control laws implemented using full-order observers. The implementation of reduced-order observers was considered; in particular, the relationship between the measurement variable and estimator state, and the effect sampling speed has on estimator gains.

While the application of digital feedback control schemes to multi-mode structures seems limited due to computation complexity and the accompanying reduction in bandwidth for systems of high order, digital MIMO control methods can be applied with reasonable success and improved performance over similar single-input methods. These experiments demonstrated reductions in a vibration-energy metric to as much as 20% of open-loop values over bandwidth. Reductions in performance were noted and believed to relate to actuator placement. Further improvements in sampling speed should improve the state estimate and provide better control and can be achieved by reducing the number of multiples executed each time step. Reduced-order observers can be implemented but considerations should be placed on the type of measurement (position and velocity) that is going to be used in the feedback compensator. Position measurements used to determine velocity states typically require large gains to place observer poles and subsequently amplify noise through the estimator feed-through term.

7.1.3 HYBRID STRUCTURAL CONTROL

A hybrid structural control architecture that combines feedback-based transient suppression and robust narrowband disturbance compensation using adaptive filtering methods has been developed [59 and 60]. A general formulation of the controller was investigated without regard to specific feedback or adaptive feedforward algorithms. The key features of feedback and feedforward control approaches are highlighted in Table 1.

Control Approach	Advantages	Disadvantages
Adaptive Feedforward Control	error signal is typically driven to zero.	Transient suppression is difficult
	large stability bounds	coherent reference required
	no modelling required	
Feedback Control	active damping provides transient suppression	modelling uncertainty leads to robustness problems

Table 1 Comparison of Adaptive Feedforward and Feedback Control.

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It has been shown that the inclusion of a feedback loop around an adaptive feedforward path leads to faster convergence times of the adaptive compensator. The improved convergence characteristics are quite important to the performance of the adaptive control in the presence of impulsive disturbances. An important contribution of the proposed hybrid controller is the generation of an controllable reference signal for the adaptive filter via an estimate of the disturbance(s) from a Kalman filter. The functional diagram of the proposed hybrid controller is illustrated in Figure 36. Analysis of the hybrid compensator demonstrates that the new control law functions as an adaptive feedback controller when the estimated disturbance is used for the reference signal. Demonstrations of the hybrid control system have been completed for a simply-supported plate subject to a mixed transient and persistent, narrowband disturbance. Numerical and experimental results are based on implementing a Discrete Linear Quadratic Gaussian (DLQG) regulator design for the feedback loop and the Filtered-X LMS adaptive feedforward algorithm. The simulation and experimental results confirm improved convergence properties, stability and performance robustness of disturbance compensation and reduced sensitivity of the adaptive filter to transient disturbances for the hybrid implementation. Figure 37 presents the results for a transient disturbance using the hybrid and Filter-X approaches. The hybrid controller is able to recover quite quickly because of the active damping component of the control signal. The FXLMS controller shows less ability to maintain performance in the presence of the transient disturbance.
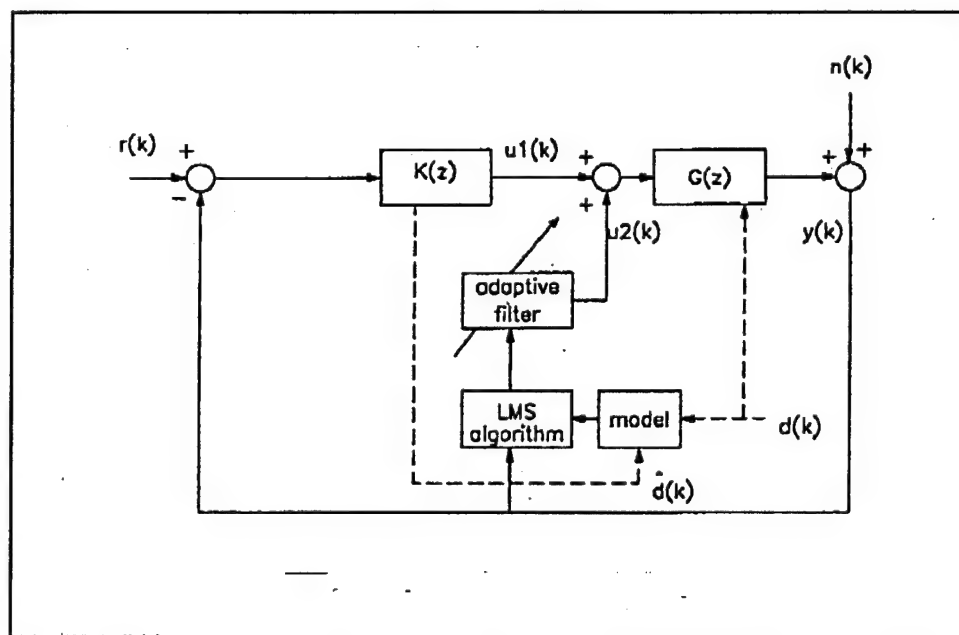
Figure 36 Hybrid control architecture.

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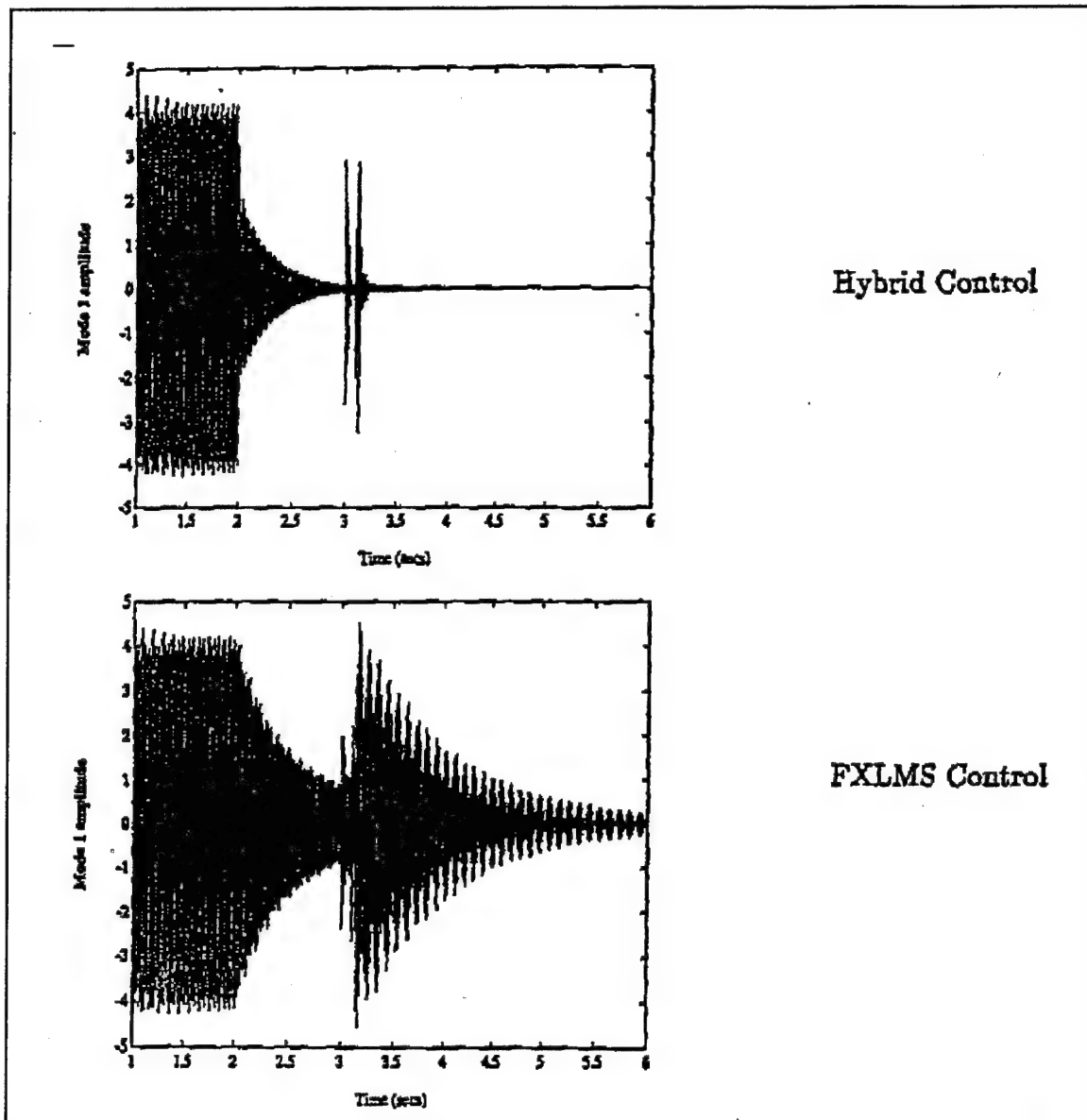
Figure 37 Effect of transient on disturbance rejection.

7.1.4 MIMO FEEDBACK CONTROL OF PIEZOSTRUCTURES

Control design for flexible structures relies on accurate modeling of the system dynamics without more advanced adaptive or robust design approaches. Typically, test models lead to improved performance over purely analytical models derived from closed-form solutions or finite-element calculations. The research here has used an approximate method for modal analysis of a piezostructure testbed to generate a dynamic model for closed-loop MIMO feedback controller design [61]. An innovative pole-residue system model for structures instrumented with piezoelectric sensors and actuators was developed which is compatible with existing curve-fitting algorithms. A

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representative curve fitting result is illustrated in Figure 38. A transformation between the pole residue model for traditional structures and piezostructures has been shown which relates the structures modal matrix and its electro-mechanical coupling (EMC) matrix [62]. Experimental measurements yield the EMC matrix. The use of the new pole-residue model without truly collocated response information has been examined. It has been shown that nearly-collocated measurements may be used to estimate a structure's modal parameters thus avoiding high precision electronics as required for exact drive-point response measurements. A simply supported plate is used to demonstrate the approximate piezostructure modal test approach. The test model was then used to design up to a four input, sixteen channel output MIMO feedback control experiment, and Figure 39 shows typical closed-loop frequency responses for a series of control configurations. Closed-loop results show that more than 10 dB of suppression is achieved near structural resonances within the control bandwidth of 10 to 250 Hz.
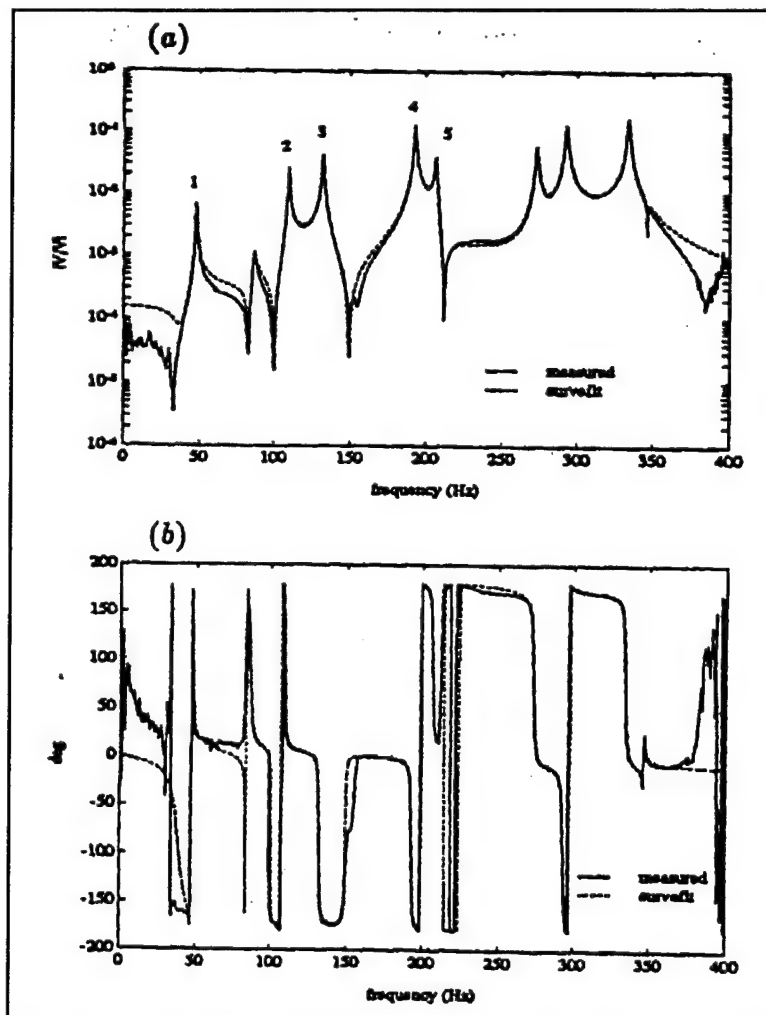
Figure 38 Curve fit and experimental FRF's for sensor #13.
(a) magnitude, (b) phase.

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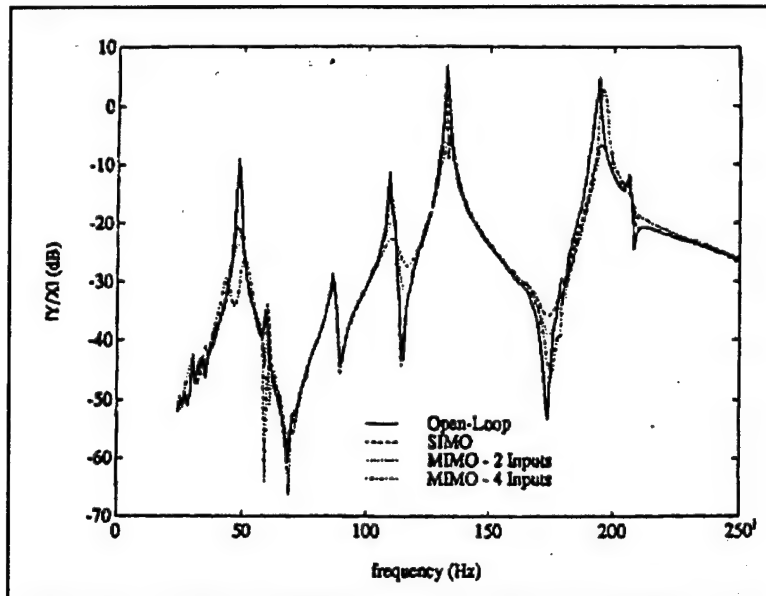
Figure 39 Closed-loop frequency response for MIMO controllers.

7.2 LMS ADAPTIVE ALGORITHMS

In general, LMS adaptive approaches rely on constructing a quadratic cost function by squaring the modules of the error variables and then using various techniques such as steepest descent, pattern search, etc., to find the unique minimum of the cost function [53]. The control approach may be implemented in both the time or frequency domains. An advantage of the LMS approach is that unlike optimal control, little system identification is needed.

The LMS adaptive Filtered-X algorithm remains the basis for most active structural acoustic control approaches, and VPI&SU has made progress in expanding the application of this popular feedforward algorithm during this Grant performance period. No only have new applications been put forward, but the complexity of the implementations of algorithm architectures and functions has increased as well. VPI&SU has tried to stay abreast of the state-of-the-art in DSP hardware available to take advantage of the ever increased processor speeds and reduced cost. New variants of the Filtered-X algorithm are always under development to make particular implementations more robust with improved performance. The many active structural acoustic applications in this report highlight some Filtered-X applications.

7.2.1 CAUSALITY OF FEEDFORWARD CONTROL

Feedforward control system causality is not an issue when a disturbance excitation is sinusoidal because of its deterministic nature. However, causality is a very important factor in broadband control. Though significant deteriorations in performance of noncausal control systems have been reported in the literature, analytical tools are virtually nonexistent to predict the behavior of

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broadband controllers. This research has developed an approach to investigate system causality. A formulation is presented to address the effectiveness of a control configuration as a function of the filter size, delay time, and dynamic properties of the structure [63]. A functional diagram of the control concept with a time delay shown in the control path is illustrated Figure 40. The technique is illustrated in a simple numerical example and the results are also corroborated experimentally.
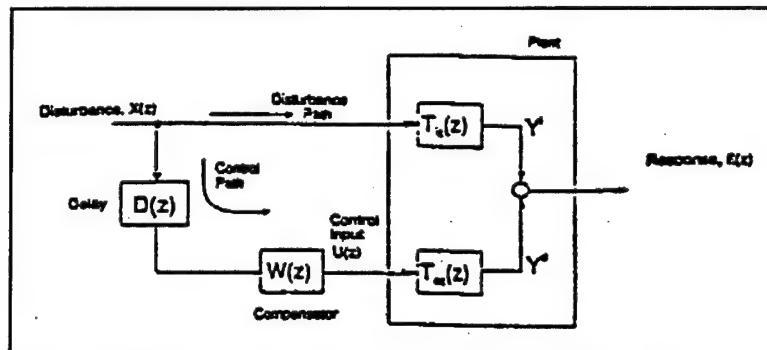
Figure 40 Discrete time domain feedforward block diagram with a delay in the control path.

In practical implementation of digital controllers, the total path delay is due to the smoothing filters, the sampling process for the controller, and the physical system itself. A causal controller can often be achieved by carefully choosing the distances between the disturbance and control inputs and the error sensors. This particularly true in active control of acoustic enclosures (in air) where the wave speed is relatively low and the physical dimensions of the system are large. However, a casual system would be difficult to realize in many other situations, i.e., in active control of structural vibrations where wave speeds are much higher.

The analysis method was developed in the frequency domain, and can be used to predict the performance of the feedforward FIR filter type controller in terms of system parameters such as delay time, damping, spectral content of the input, filter size, and etc. It was demonstrated that reduction in the error signal mean square value is always achievable for any noncausal control system. The analysis also shows that the deterioration in control performance due to the delay in the control path can be at least partially compensated by increasing the compensator order.

The general arrangement for a broadband feedforward controller experiment is shown in Figure 41 that shows a functional diagram as will as the setup for a simply supported beam. For a representative result Figure 42 illustrates the analytical and experimental power reduction results for various filter sizes, which support the above observation. The agreement between theory and experiment is seen to be reasonable.

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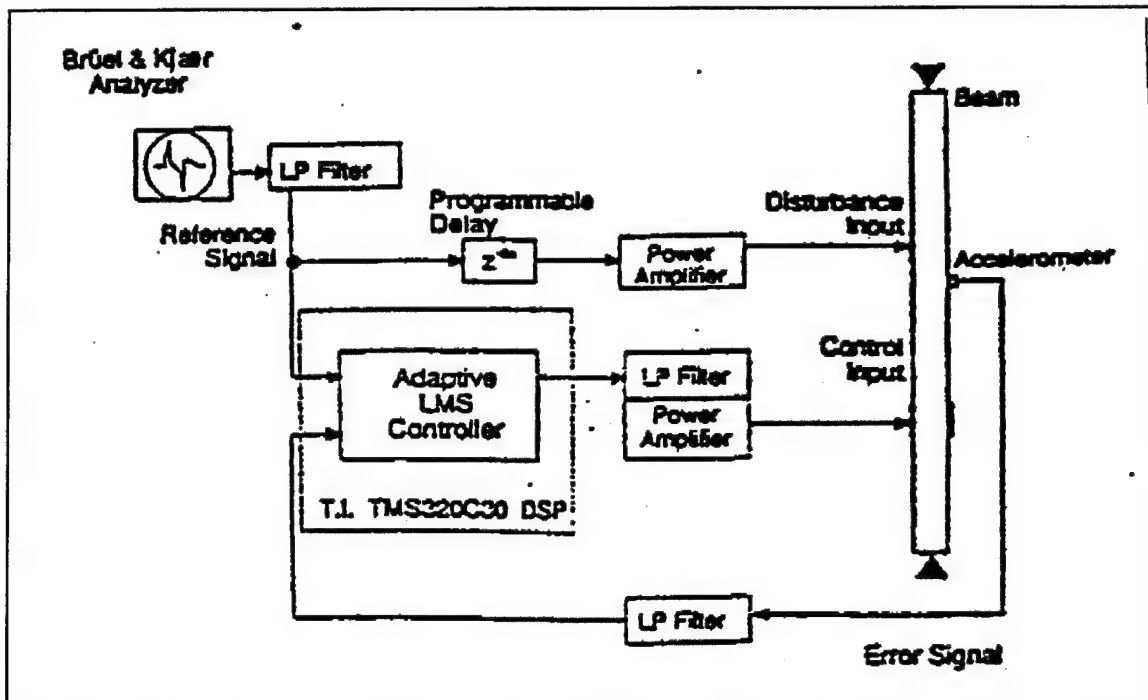
Figure 41 Experimental setup for testing the feedforward broadband control algorithm.
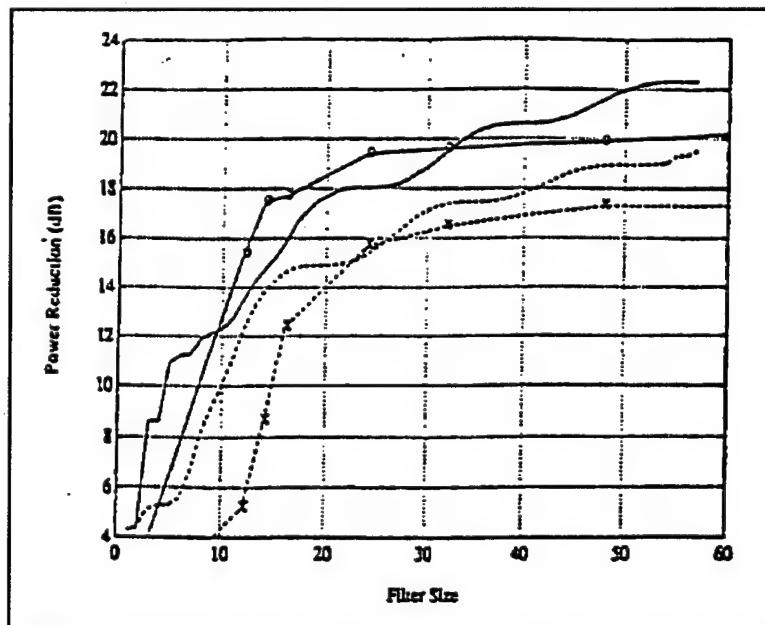
Figure 42 Power reduction of error signal as a function of the filter size. _____ Analytical casual; _ _ _ _ analytical noncausal; o-o experimental casual; x-x experimental noncausal system.

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7.2.2 BROADBAND FEEDFORWARD CONTROL

VPI&SU continues to improve adaptive feedforward controller designs for use in MIMO broadband control problems. One implementation has incorporated an Infinite Impulse Response (IIR) filter for compensating a broadband multichannel adaptive Filtered-X algorithm over a large bandwidth [23]. The primary feedforward filter is an adaptive FIR filter. The IIR compensating filter has the advantage of being more computationally efficient than a FIR compensating filter typically used. A compensating filter represents an estimate of the control path transfer function that is typically directly measured from the system. The control actuator is driven with bandlimited white noise and the transfer function between the control input and the error sensor output is measured in the frequency domain. An IIR filter is designed to model this transfer function so that it yields the same frequency response function. The IIR filter is designed by a curve-fit technique that solves a system of equations to gain the pole and zero coefficients. If the IIR design process yields poles that lay outside the unit circle that could cause instability, the poles are "reciprocated" across the unit circle into the stable region. This distorts the phase response of the model somewhat, but inversion of a small number of slightly unstable poles in a large model still yields a model with a satisfactory match of both magnitude and phase.

This implementation has been experimentally demonstrated controlling acoustic radiation from a simply supported plate with up to three control PZT actuators, and three PVDF or microphone error sensors over a bandwidth of 0 to 400 Hz. A broadband (i.e., 0-400 Hz) disturbance signal was applied to the plate with a single shaker that excited the five natural modes of plate vibrations. The 3I3O controller was implemented with a TMS320C30 DSP chip using a sampling rate of 1500 Hz. The adaptive FIR filters each contained 100 coefficients. IIR filters used for system identification of the control path transfer function had 50 zeros and 49 poles that provided an accurate model in phase and magnitude.

The experimental results were presented in Section 4.1 that addressed optimum actuator and sensor placement issues. In summary, the experimental results show limited reduction in farfield acoustic radiation for a SISO configuration. This is because the SISO controller is unable to observe and control all radiating plate modes over the frequency band. When the controller configuration was extended to 2I2O, an average sound reduction of 11 dB at all directions was obtained. Further extension of the controller configuration to 3I3O provided only an average 1 dB improvement. The results for microphones and PVDF error sensors produced similar results.

8.0 TECHNOLOGY TRANSFER

This section provides a short discussion of the issues in transferring the developed technologies to real world and practical applications.

This project sponsored the second conference on "Recent Advances in Active Control of Sound and Vibration" held at VPI&SU in April 1993. The conference was attended by many researchers and interested professionals from academia, industry, and government (250+ people). Over 80 papers were presented by U.S. and foreign researchers, and this Grant supported several presentations by VPI&SU. The conference clearly demonstrates the level of activity in this rapidly advancing technology. It additionally provided VPI&SU the opportunity to exhibit and demonstrate ongoing ONR research, and conduct working level technical exchanges with many other researchers and potential users of the technology. The industrial interest in the active structural acoustic research at VPI&SU was exceptional.

VPI&SU has worked during this Grant period with several defense contractors with serious interests in the practical application of active structural acoustic control and adaptive materials to real world problems. General active structural acoustic control (ASAC) technologies were furnished to United Technologies Research Center (UTRC), and Lord Corp for applications ranging from compressor noise, helicopter cabin noise, lift noise, and propeller aircraft interior noise. Technology on the control of interior aircraft noise was transferred to Cessna Aircraft, General Dynamic's Electric Boat Division was particularly interested in VPI&SU research in the area of wavenumber control. Noise Cancellation Technology (NCT) for specific technology transfers and developments applicable to transformer quieting. VPI&SU continuously promotes the transfer of this research to industry where it can be further developed into useful and state-of-the-art products and applications.

Active structural acoustic control and adaptive/smart material technologies can have a significant impact upon underwater acoustics and naval vessel designs in the future. Sufficient basic research progress has been conducted to show that gains can be made in near-term applications such as: low frequency radiated noise, sonar self-noise, and interior airborne noise. Also, obviously to realize the optimum and full potential of these technologies they should be incorporated into the structural design rather than retrofitted into existing systems to cure design deficiencies. The U.S. Navy should advance and demonstrate active structural acoustic control and adaptive material technologies to the point that good engineering tradeoffs can be carried out in the original design processes.

9.0 FUTURE DIRECTIONS

Future research in active structural acoustic control requires further advances with complex structures, disturbances, and more realistic design applications. This requires a highly coordinated and integrated technical effort as demonstrated during the three-year period of this Grant.

This research project has addressed narrowband and broadband disturbances, but for simplified situations. More realistic disturbance sources and characteristics need to be addressed, and understood in terms of active control system design methods and approaches. Of particular importance is understanding the degrees of freedom that can exist in real world applications, and how they acoustically radiate to the farfield.

This research effort has demonstrated real-time wavenumber domain techniques in the design of active structural acoustic control systems, and this work will be further developed. The implementation of real-time wavenumber domain active control for large scale and realistic structural problems is being pursued particularly for cylindrical structures.

Further studies are required in the optimal configuration of systems applied to structures with some degree of complexities, which additionally offer a high degree of robustness. This requires a more in-depth examination of actuator and sensor placement, and the impact of a broad number of system design temporal and spatial issues. In all structural acoustic application areas fluid-loading needs to be considered, and incorporated into the design of optimal active control system designs.

A major structural acoustic area that requires further development is the optimum integration of passive and active techniques that are applicable for large bandwidths, complex structures, and isolation systems. Active control systems can greatly benefit from the proper application of passive techniques such as gaining better power efficiencies and stability. An important direction in active structural control is the development of optimal passive-active design techniques to maximize the benefits of both technologies in a complimentary fashion. This can be particularly important for maximizing the benefits of the two techniques as a function of frequency and for particular degrees of freedom (e.g., directions). In some applications it is essential that a passive means of acoustic radiation control exist, and commonly passive structural properties may be essential for other mechanical purposes such as for example static strength and shock protection.

There is the need for developing compact low frequency actuators, and actuators that can be used as high acoustic power volumetric sources. Actuator power efficiencies are critical for practical low frequency applications, and the research here has demonstrated some promising directions that can be taken for optimizing power consumption for multiple actuator applications.

Adaptive materials and structures are gaining in importance with the wider use of basic composite structural materials, and further work is required in the development of new innovative designs of both actuators and sensors. More progress is required on the development of new theories and methods for active/adaptive distributed actuators and sensors as applied to the more complex

structures that are inherently offered by composite materials. Research needs to move in the direction of comprehensive and integrated intelligent structural, and control system designs and architectures. This will require the integration of sensing, actuation, and signal processing functions within materials and structures. VPI&SU has initiated the development of active acoustic foam that combines sensing, actuation, and passive acoustic properties into a single material structure, and this work needs to be further developed.

This research effort has shown the merits of the more conventional adaptive LMS and control theory approaches, and this work needs to be further advanced to handle the more complex and higher dimensional problems. There is the need to develop nonlinear control approaches such as artificial neural networks (ANN) that can deal with complex situations where conventional control approaches are impossible or are too complex to pursue and implement. There are many vibration problems that are inherently nonlinear in nature.

10.0 CONCLUSIONS

The results presented here show that significant progress has been made toward both understanding the mechanisms of active structural acoustic control and ultimately implementing the technique in realistic situations. With this, new understanding in the individual areas of distributed actuators and sensors and control theory and implementation as related to the structural acoustic problem has been achieved. The technique shows much potential for efficiently actively/adaptively controlling structure-borne noise radiation in many situations.

This project has made significant progress in the development of ASAC system design techniques that can be applied to a wide vanity of applications. The analytical tools and approaches developed provide a means of evaluating design alternatives, expected measures of acoustic control performance, and the resources required. The design techniques have made important progress in addressing complex structures and realistic broadband disturbances. Results of this research have been presented in 63 technical papers (including 32 papers in refereed journals), and 16 talks at symposia and conferences.

The key technical accomplishments under this Grant have advanced the state-of-the-art in structural acoustics, adaptive materials and structures, and active control. Concisely some important accomplishments are:

1. Application of real-time broadband wavenumber transforms to planar and cylindrical structures thus eliminating the need for the need for far-field sensing of the radiated sound pressure.

2. Broadband control of sound radiation from panels with integrated optimally designed actuators and sensors over the frequency range between 0 to 500 Hz.

3. Actuator and sensor design for ASAC by eigenfunction assignment extending it to MIMO feedforward controlled systems.

4. Development of FEM/BEM based efficient optimization system design approaches for ASAC with statistical diagnostics.

5. Application of hybrid structural feedforward and feedback control techniques for control of broadband acoustics to account for transient disturbances.

6. Continued development of design approaches and algorithms for the optimal placement of point force and distributed PZT actuators for actively controlling acoustic radiation from plates, cylinders, and more complex structures.

7. Similarly, developed the design techniques for the optimal placement of point accelerometer, and distributed PVDF sensors for single and multiple frequency excitation.

8. Developed optimal design approaches using FEM/BEM for complex structures under multiple frequency excitation.

9. Developed a model for active control of sound radiation from a coupled cylinder-raft system using passive-active isolation mounts.

10. Developed an eigen-analysis approach for designing shaped PVDF distributed structural acoustic sensors

11. Extended the capability of the NASUHA numerical structural acoustic model to address active control approaches for fluid loaded structures.

12. Established an electro-mechanical impedance theory for distributed strain actuation active structures with experimental verification.

13. Application of the electro-mechanical impedance theory to determine system power flow, and to design energy efficient active control structures.

14. Investigated electro-mechanical impedance theory for active structures with multiple coupled actuators.

15. Active noise control with PVDF-foam composites combining passive and active control.

16. Developed approaches to reduce the effect of aliasing in wavenumber sensing using point sensors.

17. Development of simultaneous sensing and actuation for a single piezoelectric element that provides truly collocated active control of acoustic properties.

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APPENDIX A

PROJECT PARTICIPANTS

Full Time Personnel

Dr. C. R. Fuller   Professor, P.I.
Dr. R. A. Burdisso   Professor
Dr. C. A. Rogers   Professor
Dr. H. H Robertshaw   Professor
Dr. W. T. Baumann   Professor
Dr. H. H. Cudney   Professor
D. Williams   Program Manager and Programs Grants Administrator
Dr. M. J. Bronzel *   Research Associate
Dr. R. L. Clark *   Research Associate
Dr. C. Liang *   Research Scientist
Dr. W. W. Saunders *Research Associate
Dr. Z. A. Chaudry   Research Scientist
C. White   Research Associate
J. S. Vipperman   Research Associate
S. Booth   Research Associate

Graduate Students

		Advisor
Bertrand Brévart	Ph.D.: Active Control of Coupled Wave Propagation in Fluid-Filled Elastic Cylindrical Shells, December 1994	CRF
Chris Ruckman *	Ph.D.: A Regression-Based Approach for Simulating Feedforward Active Noise Control with Application to Fluid-Structure Interactions, August 1993.	CRF
Tao Song	Ph.D.: Optimization of Transducers for Active Structural Acoustic Control of Sound Radiation from Elastic Plates Under Multiple-Frequency Excitation, January 1995.	CRF
Su-Wei Zhou	Ph.D.: A Coupled Electro-Mechanical System Modeling and Experimental Investigation of Piezoelectric Actuator-Driven Adaptive Structures, August 1994.	CAR
Cassandra Gentry	Ph.D. (AASERT)	CRF
Zhonglin Li	Ph.D.	CRF
Julian Maillard	Ph. D.	CRF
Dan Cole	Ph.D.	HHR
Héctor Rodiguez	Ph.D. (AASERT)	RAB

Jeffrey S. Vipperman	M.S.: Adaptive Feedforward Control of Broadband Structural Vibration, June 1992.	RAB
Jerome P. Smith	M.S.: Active Control of Broadband Acoustic Radiation from Structures, August 1993.	RAB
Denny Davis	M.S.: Optimization of Transducers for Active Structural Acoustic Control of Complex Structures Using Numerical Techniques, April 1994	CRF
Eric Toffin	M.S.: Active Control of a Coupled Plate-Cylinder System, April 1994	CRF
Sam Beyene	M.S.	RAB
John Risi	M.S.	RAB
Eddie Whittington	M.S.	CRF
Florence Deneufve	M.S.	CRF
Yi Feng Tu	M.S.	CRF
Mark Lin		CAR
Steve Stein		CAR
F. S. Ho		WTB

*Dr. M. J. Bronzel now has an academic position at TUDresden, Dresden, Germany.
*Dr. R. L. Clark is now an Assistant Professor at the Duke University of North Carolina, Durham, NC.
*Dr. C. Liang is now an Assistant Professor at the California University of San Diego, San Diego, CA.
*Dr. W. W. Saunders is now an Assistant Professor at the Virginia Polytechnic Institute and State University, Blacksburg, VA.
*Chris Ruckman is now a Research Fellow at the Naval Surface Warfare Center, Carderock Division, MD.

AWARDS:

Prof. C. R. Fuller won a prize from ASME for a Best Journal Paper of 1993 on Adaptive Systems.

Prof. C. R. Fuller was elected a Fellow of the Acoustical Society of America.

Prof. C. A. Rogers received the 1993 ASME Adaptive Structures and Material Systems Prize for lifetime achievement in the field of intelligent material systems. and structures.

Daniel G. Cole was awarded a Cunningham Fellowship for his doctoral studies.

Dr. Robert Clark won the Outstanding Paper by a Young Presenter in Noise Award at the 125th Meeting of the Acoustical Society of America for his

paper entitled "Active Structural Acoustic Control of Cylinder Radiation with Piezoelectric Actuators and PVDF Sensors."

APPENDIX B

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C. R. Fuller. Control of Sound Radiation with Adaptive Structures. 1994. Keynote address, SPIE Conference on Smart Structures and Materials, Orlando, FL, 13-18 February 1994.

C. R. Fuller and R. A. Burdisso. 1994. Design of Active Control Systems Using Eigenanalysis. Keynote address, Third International Congress on Air- and Structure-Borne Sound and Vibration, Montreal, Canada, 13-15 June 1994.

C. R. Fuller. 1994. Recent Developments in Active Control of Vibrations. Keynote address, Nordic Conference on Vehicle and Machine Vibrations, Stockholm, Sweden, 6-8 September 1994.

C. R. Fuller and B. J. Brévart. 1995. Active Control of Coupled Wave Propagation and Associated Power in Fluid-Filled Elastic Long Pipes. Plenary presentation, ACTIVE 95, Newport Beach, CA, July 6-8, 1995.

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